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INFLUENCE OF AXIAL AND RADIAL CLEARANCES ON THE PERFORMANCE OF A TURBINE STAGE WITH BLUNT EDGE NON-TWISTED BLADES

by

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ABSTRACT

This thesis was undertaken to determine the effects of axial and radial clearances on the performance of a single stage turbine with blunt leading edges and non-twisted blades. A series of tests was conducted on the so-called Mod II Turbine using the Transonic Turbine Test Rig of the Turbo-Propulsion Laboratory, Department of Aeronautics, of the Naval Postgraduate School. The results of these tests are presented together with a comparison of the experimental results and results predicted by a three-dimensional turbine performance calculating method. In addition, measured flow conditions upstream of the stator, between the stator and the rotor, and at the rotor discharge are presented and compared with predicted values.

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Symbols

A	Cross-sectional area (in^2)
a	Flow channel throat diameter (in)
C	Conversion factor, $2gJc_p$ (ft^2/sec^2-^0R)
c_p	Specific heat at constant pressure for air (0.24 BTU/lb_m-^0R)
D	Diameter (in.)
F	Force (lb_f)
g	Gravitational constant (32.174 lb_m-ft/lb_f-sec^2)
H	Total enthalpy (BTU/lb_m)
h	Blade height (in.)
h	Static enthalpy (BTU/lb_m)
HP	Horsepower
$\vec{i}$	Unit vector
J	Conversion factor (778.16 ft-lb_f/BTU)
$\vec{j}$	Unit vector
$\vec{k}$	Unit vector
k_{is}	Isentropic head coefficient (dimensionless)
M	Moment (ft-lb_f)
M	Absolute Mach number (dimensionless)
M_R	Relative Mach number (dimensionless)
$\dot{m}$	Mass flow rate (slugs/sec)
N	Rotational speed (RPM)
$\hat{n}$	Unit vector directed outward from a surface
P_t	Total pressure (psia)
p	Static pressure (psia)
R_G	Gas constant for air (53.345 ft-lb_f/lb_m-^0R)

R_m Root mean square radius (in.)

r Radius (in.)

r^* Theoretical degree of reaction (dimensionless)

S Surface where fluid enters or leaves a control volume ($in.^2$)

s Distance between blades (in.)

s Entropy (BTU/lb_m-^oR)

T Static temperature (^oR)

T_t Total temperature (^oR)

t_e Blade thickness at the trailing edge (in.)

U Peripheral velocity (ft/sec)

V Absolute velocity (ft/sec)

W Relative velocity (ft/sec)

W Flow rate (lb_m/sec)

Z Number of blades in a blade row

Greek Letters

α Absolute flow discharge angle (degrees)

β Relative flow discharge angle (degrees)

γ Ratio of specific heats for air (1.401)

δ Referred pressure ratio (dimensionless)

ζ Loss coefficient (dimensionless)

η Efficiency (dimensionless)

θ Referred temperature ratio (dimensionless)

ξ Area restriction factor or blockage factor (dimensionless)

ρ Density (lb_m/sec)

ϕ Flow function (dimensionless)

ω Angular velocity (radians/sec)

Subscripts

a	Axial direction
ax	Area normal to the axial direction
CL	Closure plate
E	Equivalent thermodynamic property
h	Blade hub
i	In the axial direction or around the machine axis
is	Isentropic
L	Labyrinth seals
m	Mean streamline
N	Properties at the flow measuring nozzle
o	Properties at the entrance to stator blades
P	Properties in the plenum ahead of stator assembly
p	Denotes forces due to pressure
R	Rotor
r	Radial direction
REF	Referred value
S	Stator
t	Blade tip
TH	Theoretical value
u	Peripheral direction
1	Properties at the exit of the stator
2	Properties at the exit of the rotor

1. Introduction

The Mod II Turbine is a test model of the fuel pump drive turbine designed by Professor M. H. Vavra of the Department of Aeronautics, Naval Postgraduate School, for an advanced liquid rocket engine. It was designed for good off-design point performance, ruggedness, and simplicity. Good off-design point performance was needed because the rocket was to produce variable thrust over a large percent variation of full thrust. Ruggedness was a design criteria because the rocket must endure stop-start operations. Simplicity of design provides ease of manufacture and low unit cost. In addition, the Mod II Turbine was designed to allow for adequate space in the blades for internal cooling passages. The foregoing considerations lead to a turbine design with thick non-twisted blades which have blunt leading edges.

The amount of test data which is available on turbine designs of this type is very limited. Turbine designers have a particular need to know what effects are induced in turbine performance by varied clearances between the stator and rotor and between the rotor tips and the shroud. This project hopefully helps fill this need.

The Transonic Turbine Test Rig located at the Aeronautics Propulsion Laboratory of the Naval Postgraduate School provides a unique test bed for determining the effects of axial and radial clearances on the performance of turbines at varied pressure ratios and speeds. This report covers the testing of the Mod II Turbine in the Test Rig at two radial clearances, five axial clearances, four pressure ratios, and varied rotational speeds between 10,000 and 19,000 RPM.

The author is very appreciative of the many hours of cheerful assistance during the equipment set-up and data acquisition given by

Mr. Jim Hammer of the Department of Aeronautics. Also, the willing assistance of Lt. P. M. Commons, U.S.N. and the helpful advice given by Lt. R. H. Harrison, U.S.N. are greatly appreciated. Particular thanks are given to Professor Vavra for his patient instruction and guidance.

2. Turbine Description

Figures 1, 2, and 3, and Figures 4, 5, and 6 are photographs of the Mod II Turbine stator and rotor, respectively. The turbine is a single stage unit of the reaction type. Pertinent turbine dimensions are listed in Table I together with the design point performance parameters. Unless otherwise specified, the values in Table I refer to the mean blade radius. Most of the dimensions given in Table I are self-explanatory; however, the following quantities need to be defined more clearly. The throat diameter, a, shown in Fig. 7, is the minimum distance between the blades at the mean radius. The throat area, A_{th}, is defined as

$$A_{th} = z a h \tag{1}$$

Definitions of the absolute and relative exit angles, α and β, are shown in Fig. 8. Figure 8 depicts the so-called velocity triangles for the Mod II Turbine at the design conditions. All angles are measured from the axis. Positive angles are measured to velocity vectors with peripheral components in the direction of the rotor rotational speed vector, $\vec{U}$. Definitions of the loss coefficients and other performance parameters listed in Table I are presented in Section 4. During the designing of a turbine, loss coefficients must be assumed in order to determine proper areas for the flow channels.

Large losses can result from improper area design. Turbine designers usually use experimentally determined loss coefficients. The loss coefficients used in designing the Mod II Turbine and listed in Table I were derived from experimental data presented by Klein[1].

3. Test Installation

The turbine was tested on the Transonic Turbine Test Rig, hereafter referred to as the TTR. The TTR is designed and instrumented to determine the performance characteristics of a turbine stage at varied axial and radial clearances, and to measure the flow properties before and after each blade row. It has the unique capability of determining mean flow conditions in a turbine without introducing flow disturbing probes into the flow stream. Detailed descriptions of the TTR installation, instrumentation and data reduction techniques are presented by Commons[2]. This discussion will be limited to the salient features of the TTR from which performance data on the Mod II Turbine were obtained.

Compressed air is used as the working fluid in the TTR. It is supplied by a twelve stage axial compressor located in a test cell adjacent to the TTR. The supply air enters the TTR test cell at the inlet valve for Tank 1 as shown in Fig. 9. Tank 1 is a settling tank and plenum chamber for the exhauster and for Tank 2. The exhauster is used to lower the pressure in the test hood below atmosphere to obtain large pressure ratios across the turbine being tested.

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[1] Klein, Armin, Experimentelle Nachprüfung eines Berechnungsverfahrens für axiale Strömungsmaschinen am Beispiel einer Turbinenstufe. Forschg. Ing-Wes. 31 (1965) Nr. 5.

[2] Commons, P. M., Instrumentation of the Transonic Turbine Test Rig to Determine the Performance of Turbine Inlet Guide Vanes by the Application of the Momentum and Moment of Momentum Equations (NPGS Thesis, Sept. 1967).

Air for the turbine leaves Tank 1 through the flow rate nozzle and goes into Tank 2 which is the settling tank for the turbine plenum. The flow rate nozzle is instrumented with total pressure taps and a total temperature probe ahead of the nozzle and static pressure taps downstream of the nozzle. The air path from Tank 2, through the turbine inlet valve, and into the test hood to the turbine plenum is shown in Fig. 9.

Figure 10 is a cross-section of the arrangement inside the test hood. The turbine plenum is supported independently from the stator assembly and surrounds the upstream end of the stator assembly. The plenum is instrumented with total temperature and total pressure probes. A small amount of air leaks from the plenum through the labyrinths that seal the plenum pressure from the pressure inside the hood. Air flows radially from the plenum into the stator assembly, thence through the turbulence reduction screens to the stator. Six fixed total pressure probes and two moveable total pressure and temperature Kiel probes are located between the screens and the stator. The total pressure probes are fixed at a radial distance which approximately divides the flow entering the stator into equal mass flow rate increments. The fixed probes and the conical turbulence reduction screens are shown in Fig. 11.

The closure plate, shown in Fig. 12, is attached to the stator assembly by a cylindrical member and a spoked wheel type flexure device, which is instrumented with strain gages to determine the torque and the axial force transmitted from the closure plate to the stator assembly. Also, the cavity between the closure plate and the stator assembly is instrumented with a static pressure port.

Static pressure ports are arranged along the shroud at ¼-inch intervals beginning at the exit of the stator. The arrangement of these ports on the downstream end of the shroud is shown in Fig. 12.

The radial clearance between the rotor tips and the shroud is determined by the inside diameter of the shroud. Different shrouds are available for installation on the test rig to provide varied radial clearances.

The entire stator assembly is supported by flexures which allow the assembly to move in the axial direction and around the axis. Reluctance type force gages are located between the moveable stator assembly and the fixed structure. The force gages measure the axial force, and the moment about the axis, which are transmitted from the moveable stator assembly to the fixed structure.

The rotor is cantilevered from the rotor bearing support stand. Figure 14 shows the rotor mounted in the bearing stand. Two sets of matched precision ball bearings support the rotor shaft. The bearings are lubricated by an oil mist system.

The axial distance between the stator and rotor is varied by sliding the rotor bearing assembly in the support stand. The bolt at the top of the rotor bearing support stand locks the sliding assembly in the desired axial position.

A quill shaft connects the rotor shaft to the dynamometer shaft. A six-spoked flux cutter is fitted to the dynamometer end of the quill shaft. The flux cutter passes through the field of a magnetic pickup from which the RPM of the rotor is obtained.

The dynamometer is an air brake device which is cantilevered from the dynamometer bearing support stand. The dynamometer bearings are similar to the rotor bearings. A twenty inch long arm is attached

to the shaft between the dynamometer bearing stand and the dynamometer. The arm acts on a reluctance type force gage from which the dynamometer torque is determined. Table II lists the quantities recorded during a performance test run. All pressures are measured on a mercury manometer, except the pressure differential across the flow nozzle which is read on a water filled, U-tube. All the temperatures are obtained from Iron-Constantan thermocouples referenced to an ice bath.

4. Analysis and Data Reduction.

General

The turbine performance data were analyzed with a one-dimensional mean streamline approach. Steady axisymmetric flow conditions were assumed to exist at the entrance and discharge of each blade row. Adiabatic flow conditions were assumed to exist through the entire stage. The mean flow conditions were assumed to exist at the root mean square of the blade radii, hereafter referred to as the mean radius, R_m. The mean radius is found as

$$R_m = \left[\frac{R_t^2 + R_h^2}{2}\right]^{1/2} \text{(inches)} \qquad (2)$$

where R_t = radius of blade tip (inches)

R_h = radius of blade hub (inches).

For simplicity in the following development, the mean radius will be considered constant through the stage. In the actual calculations, the variation in mean radius between the stator blades and the rotor blades was taken into account. The major portion of the data reduction calculations was performed by the IBM 360 digital computer located at the Naval Postgraduate School.

Flow rate

The flow rate through the turbine is the flow rate through the flow measuring nozzle less the flow rate through the labyrinth seals. Thus

$$\dot{W} = \dot{W}_N - \dot{W}_L \tag{3}$$

where

$\dot{W}$ = Flow rate through the test turbine (lb_m/sec)

$\dot{W}_N$ = Flow rate through the flow measuring nozzle (lb_m/sec)

$\dot{W}_L$ = Flow rate through the labyrinth seals (lb_m/sec)

The flow rates through the flow nozzle and through the labyrinth seals are determined by measuring the applicable quantities listed in Table II. The calibration methods and data reduction formulae are discussed by Commons[3].

Stage entrance properties

The total pressure at the stator entrance, P_{to}, is taken as the average pressure indicated by the six fixed pressure probes. The validity of this assumption is explored in Sec. 7. The total temperature, T_{to}, is obtained from the Kiel probes.

Stator discharge properties

The fluid properties at the stator discharge and the stator performance parameters are obtained by determining the velocity triangle at the stator exit. The peripheral component, V_{u_1}, of the absolute velocity is obtained by application of the moment of momentum law to the fluid contained in the stator assembly. From the derivation presented in Appendix I,

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[3] Ibid, Sec, 4

$$V_{u_1} = (M_{CL} + M_S)g/\dot{W}R_m \tag{4}$$

where

V_{u_1} = Peripheral component of absolute velocity at the stator exit. (ft/sec)

M_s = Moment applied to the stator assembly by the moment capsule shown on Fig. 12. (ft-lb_f)

M_{CL} = Moment applied to the stator assembly by the closure plate (ft-lb_f)

The axial velocity component, V_{a_1}, is found by application of the conservation of momentum law to the fluid in the stator assembly. From Appendix I,

$$V_{a_1} = \frac{g}{\dot{W}}\left[F_s + F_{CL} + \Sigma F_p - 2\pi\int_{r_h}^{r_t} p_1\, r\, dr\right] \tag{5}$$

where

V_{a_1} = Axial velocity component at the stator discharge (ft/sec)

F_s = Force applied to the stator assembly by the axial force gage (See Fig. 13) (lb_f)

F_{CL} = Axial force applied to the stator assembly by the closure plate (lb_f)

F_p = Net pressure force acting on stator assembly. (lb_f) (See Appendix I, p.112).

p = Static pressure at any radius at the stator exit. ($lb_f/in.^2$) Refer to Appendix I, p.112 , for the solution to the pressure integral given in Eq. (5).

Since the continuity equation must be satisfied by the fluid flow through the stator, the axial velocity component, V_{a_1}, may be determined as,

$$V_{a_1} = \left\{ 2gJc_p \left[T_{t_0} - \frac{gJc_p A_1^2 P_1^2}{R_G^2 \dot{W}^2} \left(-1 + \left(1 - \frac{2\dot{W}^2 R_G^2}{gJc_p A_1^2 P_1^2} \left(\frac{V_{U_1}^2}{2gJc_p} - T_{t_0} \right) \right)^{1/2} \right) \right] \right\}^{1/2} \qquad (6)$$

Refer to Appendix I, p. 112, for the derivation of Eq. (6).

In the data reduction computer program, contained in Appendix II, both Eq. (5) and Eq. (6) are satisfied by an iteration procedure which determines a compatible static pressure distribution in the radial direction at the stator exit. The stator exit velocity is then found as

$$V_1 = \left[V_{a_1}^2 + V_{U_1}^2 \right]^{1/2} \qquad (7)$$

Referring to Fig. 16, the stator absolute discharge angle is

$$\alpha_1 = \mathrm{TAN}^{-1} \left(\frac{V_{U_1}}{V_{a_1}} \right) \qquad (8)$$

The relative axial velocity component is

$$W_{a_1} = V_{a_1} \qquad (9)$$

and the relative peripheral component is

$$W_{U_1} = V_{U_1} - U \quad ; \quad U = \omega R_m \qquad (10)$$

where

ω = rotor rotational speed (rad/sec)

The relative velocity is now found as

$$W_1 = \left[W_{a_1}^2 + W_{U_1}^2 \right]^{1/2} \qquad (11)$$

and the relative stator discharge angle is

$$\beta_1 = \mathrm{TAN}^{-1} \left(\frac{W_{U_1}}{W_{a_1}} \right) \qquad (12)$$

The absolute and relative Mach numbers are found as

$$M_1 = \frac{V_1}{a_1} \tag{13}$$

$$M_{R_1} = \frac{W_1}{a_1} \tag{14}$$

where a_1 is the local speed of sound at the stator exit, obtained as

$$a_1 = [g \gamma R_G T_1]^{1/2} \tag{15}$$

where

γ = specific heat ratio for air (1.401).

The effectiveness of the stator is measured by the stator loss coefficient which, referring to Fig. 15, is defined as

$$\zeta_s = \frac{T_1 - T_{1is}}{T_{t_0} - T_{1is}} \tag{16}$$

where

$T_{1_{is}}$ = static temperature at the stator discharge if the expansion process from (T_{to}, P_{to}) to p_1 were isentropic.

It can be seen on Fig. 15 that an equivalent definition for the stator loss coefficient is

$$\zeta_s = \frac{V_{1_{TH}}^2 - V_1^2}{V_{1_{TH}}^2} \tag{17}$$

where

$V_{1_{th}}$ = velocity at stator exit if expansion through the stator were isentropic.

By using the energy equation and the equation of state for an isentropic expansion

$$V_{1_{TH}}^2 = 2gJc_p T_{t_0} \left[1 - \left({p_1}/{P_{t_0}} \right)^{\frac{\gamma-1}{\gamma}} \right] \tag{18}$$

Combining Eqs. (16) and (17)

$$\zeta_s = 1 - \frac{V_1^2}{2gJc_p[1-(P_1/P_{t0})^{\frac{\gamma-1}{\gamma}}]} \tag{19}$$

ζ_s is an average value of the stator effectiveness. In the actual flow passage through the stator the major part of the losses is due to the boundary layers which form along the surfaces of the blades. In fact, expansions along streamlines away from the bounding surfaces should be nearly isentropic. For this reason, it is quite difficult to obtain a meaningful average stator loss coefficient by measuring the flow properties with probes introduced into the flow stream. Obviously, it would require a great number of points to be measured very near the surfaces. Herein lies the significant advantage of the TTR with the force capsule arrangement which gives mean flow conditions by measuring external forces on the stator assembly. The stator efficiency is given by

$$\eta_s = 1 - \zeta_s \tag{20}$$

The flow function Φ is given by Vavra[4] as

$$\Phi = \frac{\dot{W}}{A_{th} P_{t0}} \left[\frac{T_{t0} R_G}{g}\right]^{1/2} \tag{21}$$

and the isentropic flow function as

$$\Phi_{is} = \left\{ \frac{2\gamma}{\gamma-1} \left[(P_1/P_{t0})^{2/\gamma} - (P_1/P_{t0})^{\frac{\gamma+1}{\gamma}} \right] \right\}^{1/2} \tag{22}$$

The stator flow restriction factor or blockage factor is defined as

$$\xi = \frac{\Phi}{\Phi_{is}} \tag{23}$$

[4]Vavra, M. H., Problems of Fluid Mechanics in Radial Turbomachines Parts I & II. Von Karman Institute Course Note 55a. Rhode-Saint-Genese, Belgium: Von Karman Institute for Fluid Dynamics, March 1965, equation C(7).

Rotor discharge properties

By considering the flow through the rotor relative to the moving rotor blades, the fluid properties at the rotor exit can be determined in a manner quite analogous to the method applied to the flow through the stator.

The peripheral component of the relative velocity at the rotor exit is found from the moment of momentum equation. From Appendix I, p.112,

$$W_{U_2} = W_{U_1} - M_D \, g / R_m \dot{W} \tag{24}$$

where

M_D = moment measured by the dynamometer force capsule. From Appendix I, p.112 , the axial component of the relative velocity is

$$W_{a_2} = \frac{\dot{W} R_G T_2}{P_2 A_2} \tag{25}$$

where the static temperature at the rotor discharge is found by combining the energy and continuity equations as

$$T_2 = \frac{g J c_p A_2^2 P_2^2}{\dot{W}^2 R_G^2} \left\{ \left[1 - \frac{2 \dot{W}^2 R_G^2}{g J c_p A_2^2 P_2^2} \left(\frac{W_{U_2}^2}{2 g J c_p} - T_1^2 - \frac{W_1^2}{2 g J c_p} \right) \right]^{1/2} - 1 \right\} \tag{26}$$

The various velocity components and discharge angles for the rotor exit can now be computed. From Fig. 16,

$$W_2 = \left(W_{a_2}^2 + W_{U_2}^2 \right)^{1/2} \tag{27}$$

$$V_{a_2} = W_{a_2} \tag{28}$$

$$V_{U_2} = W_{U_2} + U \tag{29}$$

$$V_2 = [V_{a2}^2 + V_{u2}^2]^{1/2} \tag{30}$$

$$\beta_2 = \mathrm{TAN}^{-1} \left(\frac{W_{u2}}{W_{a2}}\right) \tag{31}$$

$$\alpha_2 = \mathrm{TAN}^{-1} \left(\frac{V_{u2}}{V_{a2}}\right) \tag{32}$$

Analogous to the stator loss coefficient, the rotor loss coefficient is defined as

$$\zeta_R = 1 - \frac{W_2^2}{W_{2_{TH}}^2} \tag{33}$$

where

$W_{2_{th}}$ = relative velocity at the rotor exit if the expansion through the rotor were isentropic, (ft/sec).

This expansion is shown in Fig. 15 from $(P_{E_1};T_E)$ to $(P_2,T_{2_{is}})$.

$W_{2_{th}}$ is calculated as

$$W_{2_{TH}} = \left\{ W_1^2 + 2gJc_p\left[1 - \left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma}\right]\right\}^{1/2} \tag{34}$$

The efficiency of the rotor is defined by

$$\eta_R = 1 - \zeta_R \tag{35}$$

Stage performance parameters

The overall efficiency of the turbine stage is that percent of the isentropic temperature drop across the stage which is used in developing work output. The isentropic temperature drop across the stage, ΔT_{is}, is shown in Fig. 15. It is computed as

$$\Delta T_{is} = T_{t_0}\left[1 - \left(\frac{P_2}{P_{t_0}}\right)^{\frac{\gamma-1}{\gamma}}\right] \tag{36}$$

ΔT_{is} is often expressed in terms of a theoretical velocity, C_o, as

$$\Delta T_{is} = \frac{C_o^2}{2gJc_p} \tag{37}$$

The temperature drop which represents the work output is shown on Fig. 15 as ΔT_w. It is computed as

$$\Delta T_w = \frac{M_D\,\omega}{\dot{W}\,c_p} \tag{38}$$

or, by Euler's turbine equation, as

$$\Delta T_w = U\left(V_{u_1} - V_{u_2}\right)/gJc_p \tag{39}$$

The efficiency is then computed as

$$\eta = \frac{\Delta T_w}{\Delta T_{is}} = \frac{2U(V_{u_1} - V_{u_2})}{C_o^2} = \frac{M_D\,\omega/\dot{w}\,c_p}{T_{t_0}\left[1 - \left(P_2/P_{t_0}\right)^{\gamma-1/\gamma}\right]} \tag{40}$$

This efficiency is known as the total to static efficiency. The isentropic expansion across the stage is considered to start at the total pressure ahead of the stage and extend to the static pressure after the stage. The kinetic energy of the fluid leaving the stage is considered as a loss.

The percent of ΔT_{is} associated with a theoretical isentropic expansion across the rotor from p_1 to p_2 is known as the theoretical degree of reaction. In terms of velocities it is defined as

$$r^* = 1 - \frac{V_{1_{TH}}^2}{C_o^2} \tag{41}$$

r^* is an important stage parameter. It is an indication of the amount of acceleration experienced by the flow in each row of blades in the turbine stage. Using Eqs. (18), (36), and (37), r^* is expressed as

$$r^* = \frac{(p_1/p_2)^{\gamma-1/\gamma} - 1}{(p_{o}/p_2)^{\gamma-1/\gamma} - 1} \tag{42}$$

The values of r^* at the hub and tip are computed by substituting p_h and p_t for p_1, in Eq. (42).

The peripheral speed of a turbine rotor, U, is usually a fixed value which is determined by the allowable stress level in the rotor blades. For this reason, U is commonly used to define dimensionless stage performance parameters.

The isentropic head coefficient, k_{is}, relates the isentropic energy change across the stage to the peripheral speed by the relation

$$k_{is} = \left(\frac{C_o}{U}\right)^2 \tag{43}$$

The work coefficient k_w relates the actual work accomplished in a stage to the peripheral speed as

$$k_w = \frac{2(V_{u_1} - V_{u_2})}{U} = \frac{\Delta T_w}{U^2/2gJc_p} \tag{44}$$

k_{is} is used by designers to estimate the number of stages necessary to handle a given isentropic energy change at any given peripheral speed, U. Similarly, k_w is used to estimate the flow rate through a stage necessary to produce a specified amount of power at any given speed U.

In order to compare the results of the performance tests from run to run, and with predicted results, the NASA reference system is employed. The reference parameters are defined as

$$\theta = {}^{\gamma R_G T_{to}}\!\Big/_{(1.401)(53.35)(518.4)} \qquad (45)$$

for air

$$\theta = {}^{T_{to}}\!\Big/_{518.4} \qquad (46)$$

and

$$\delta = {}^{P_{to}}\!\Big/_{14.7} \qquad (47)$$

The performance values which are measured on the TTR and then reduced to referred values are flow rate,

$$\dot{W}_{REF} = \dot{W}\,\frac{\sqrt{\theta}}{\delta} \qquad (lb_m/sec) \qquad (48)$$

dynamometer moment,

$$M_{D_{REF}} = {}^{M_D}\!/_{\delta} \qquad (ft\text{-}lb_f) \qquad (49)$$

horsepower,

$$HP_{REF} = {}^{HP}\!\Big/_{\delta\sqrt{\theta}} \qquad (hp) \qquad (50)$$

and rotational speed

$$N_{REF} = {}^{N}\!\Big/_{\sqrt{\theta}} \qquad (rpm) \qquad (51)$$

5. Description of Performance Tests

The performance tests were conducted from January through August 1967. The turbine was operated about 150 hours while performance data were being taken. Table III lists the test parameters used in each run.

The first series of test runs was performed at a radial clearance between the rotor tips and the shroud, Δr , of 0.033 inch. Prior to each run, the axial clearance between the stator and rotor, Δx, was set at the desired position. Five axial positions, Δx, of 0.200, 0.0410, 0.620, 1.000 and 1.500 inches, were used in the first set of tests. The second series of tests was performed at a radial clearance, Δr , of 0.015 inch. Since the changes in performance parameters with a change in axial clearance were found to be small at the original radial clearance, it was decided to conduct the final set of tests at only three axial clearances; namely, Δx of 0.200, 0.410, and 1.000 inch.

At each combination of axial clearance, Δx, and radial clearance, Δr, the turbine was tested at four pressure ratios across the stage, (P_{to}/p_2); namely, at 1.3, 1.4, 1.5, and 1.6. An additional pressure ratio, (P_{to}/p_2) of 1.45, was examined during run number 63.

The test data items shown in Table II were recorded at a number of rotational speeds, N, between 10,000 RPM and 19,000 RPM, at each combination of radial clearance, axial clearance and pressure ratio. The pressure ratios listed in Table III are approximate due to the difficulty experienced in holding exact pressure ratios while varying the RPM. This was a particular problem during the initial tests conducted with the exhauster operating. As experience was gained and better techniques were developed, it became possible to hold the pressure ratios to within one-half a percent of the desired pressure ratio.

The torque absorption capacity of the dynamometer limited the range of head coefficients, k_{is}, over which the tests could be performed. The maximum head coefficient obtained in these tests was about 3.6.

A chronological list of the test runs is given in Table IV. Also included are the important changes made on the TTR, the duration of each run, and any difficulties occuring during the run. The chief mechanical difficulties encountered were fluctuations in input pressure due to fluctuations of the axial compressor, slippage of the dynamometer torque arm during the run, and force capsule calibration changes due to changes in capsule temperature. These difficulties as well as several other minor difficulties were easily overcome by minor design changes.

Calibration checks were made on the force capsules and the dynamometer arm position at the end of each run. With this information and the stability of the input pressures during the runs, the author feels that runs 56 through 63, run 68 and run 78 yielded the most accurate performance data.

6. Results and Discussion of Performance Tests

General

A complete set of raw data and reduced performance data for TTR test runs 51 through 80 is filed in the Turbo-Propulsion Laboratory Office. Reduced data for test runs 58 through 63, 68, 77, and 78 are contained in Appendix III. The performance parameters used in Appendix III have been defined in Sec. 4. In order to illustrate particular phenomena, some of the data from Appendix III have been graphically displayed in Figs. 18 through 56. Figures 18 through 29 are plotted to show the influence of axial clearance from the stator to the rotor, Δx, on the turbine performance. The influence on the turbine performance of the radial clearance between the rotor and the shroud, Δr, is illustrated in Figs. 30 through 36. Figures 37 through 46 are graphical

comparisons between the results of test runs 59 and 68, and performance characteristics predicted for the Mod II Turbine by the three-dimensional prediction method described by Harrison[5].

Influence of axial clearance

The most important finding of this study is that the total to static stage efficiency increases with increasing axial clearance up to an axial clearance, Δx, of about 1.000 inch. This was found to be true at both radial clearances used in these tests. Figures 18 and 19 show efficiency versus referred rotor speed at a stage pressure ratio, P_{t_o}/p_2, of 1.3 for radial clearances, Δr, of 0.033 inch and 0.015 inch respectively. Data scatter in Fig. 18 precludes a quantitative analysis of the increase in efficiency with increase in axial clearance. But in Fig. 19, the data are smooth enough to state with certainty that the total to static stage efficiency increases about one point with an increase in axial clearance, Δx, from 0.200 to 1.000 inch. Similar results are shown for a pressure ratio, (P_{t_o}/p_2), of 1.4, in Figs. 20 and 21.

Equation (40) shows that for a given stage pressure ratio, P_{t_o}/p_2, a given inlet total temperature, T_{t_o}, and a given rotor speed, N, the stage efficiency is a function of the dynamometer torque, M_d, and the mass flow rate, $\dot{W}$. The influence of varied axial or radial clearance on efficiency can then be defined as a function of changes in mass flow rate and changes in dynamometer torque. By comparing referred mass flow rates, the effects of varied inlet temperature conditions need not be considered. Moreover, the changes of mass flow rate with changes in

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[5]Harrison, R. G., An Analysis of Single Stage Axial-Flow Turbine Performance Using Three-Dimensional Calculating Methods, (NPGS Thesis, Sept. 1967).

rotor speed are quite small. Therefore, for a given radial clearance, the influence of changes in axial clearance on the flow rate can be depicted by plotting referred mass flow rate as a function of pressure ratio. This was done for a radial clearance, Δr, of 0.015 inch in Fig. 23 and for a radial clearance, Δr, of 0.033 inch in Fig. 22. The conclusion drawn from Figs. 22 and 23 is that increased axial clearance has little effect on the mass flow rate.

Similarly, to show the influence of varied axial clearance on the torque produced by the turbine, the referred dynamometer moment was plotted against the referred rotor speed. These plots are shown in Figs. 24 and 25. It can be concluded from these graphs that the increase in efficiency with an increase in axial clearance is primarily the result of an increase in produced torque.

To summarize the last three paragraphs, the Mod II Turbine will operate most efficiently at an axial clearance, Δx, of 1.000 inch. At any other axial clearance the torque will decrease and the mass flow rate will remain about the same.

During the test runs, the most noticeable effect as the axial clearance was increased was an increase in the static pressure at the stator tip and a decrease in the static pressure at the stator hub. This phenomenon is apparent in all test data. The pressure change shows up in the reduced performance parameters as a change in the theoretical degree of reaction. The theoretical degree of reaction increases at the tip and mean radii and decreases at the hub radius with increasing axial clearance. To show a typical result, the theoretical degree of reaction at the tip and hub were plotted in Figs. 27 and 28 for run 78.

That the efficiency should increase with an increase in degree of reaction is quite consistent with the data shown by Fig. 26 which is taken from Vavra[6]. The isentropic head coefficient for these tests varied from a k_{is} of 1.5 to about a k_{is} of 3.5, and the theoretical degree of reaction at the mean was about 0.25. Referring to Fig. 26, an increase in r^* would be expected to increase the efficiency. The physical reason that the efficiency increases with an increase in degree of reaction is that the flow through the rotor becomes more accelerated. And a more accelerated flow means less opportunity for flow separation to occur. Knowing this, the phenomenon described above leads to the conclusion that losses are occurring in the Mod II rotor due to decelerated flow conditions.

From Δx of 1.000 to 1.500 inch there was a further increase in r^* but a slight reduction in efficiency. This would indicate that, in this range of axial clearances, the increase in losses due to the increased length of the boundary layer along the shroud and/or other effects outweighs the increase in efficiency due to the increase in the mean degree of reaction.

The reason that the pressure distribution between the stator and rotor changes with a change in axial clearance is not entirely clear. One likely possibility is that the blunt leading edges of the rotor blades causes an adjustment in the velocity field upstream of the rotor. Since the relative and absolute velocity fields between the blade rows are subsonic, the presence of the rotor can be felt upstream in the form of an induced pressure. If this is the phenomenon which raises the efficiency of the machine, the rotor must induce a pressure field which

[6]Vavra, M. H., Aero-Thermodynamics and Flow in Turbo-Machines, New York, London: John Wiley and Sons, Inc., 1960, pg. 436.

guides the flow particles into the rotor flow channel at a more optimum angle as the axial clearance is increased. It has been demonstrated with stationary cascades on a water table that the axial distance between blade rows greatly influences the stream paths of the flow particles. However, the flow through a stationary row and a moving row of blades might produce different conditions.

The change in pressure distribution may be due entirely to unsteady conditions caused by the moving rotor blades passing through the wakes of the stator blades. If this is the case, these phenomena will not be observed on a rectilinear cascade. In an unsteady flow, so-called Reynolds stresses are produced which must be added to the force field calculated from mean momentum flow. Experimental investigations about the magnitude of Reynolds stresses in turbomachines seem to be non-existent in the available literature. Further studies with the TTR and Mod II Turbine should provide some answers to these important unsteady flow questions.

Influence of radial clearance

The total to static efficiency increased from one to four percent when the radial clearance between the rotor tips and the shroud was decreased from 0.033 inch to 0.015 inch. Figures 30 through 33 show the efficiency as a function of the isentropic head coefficient for pressure ratios of 1.3, 1.4, 1.5, and 1.6. There is no clear relationship between the efficiency change and pressure ratio, RPM, or axial clearance. It can be concluded, by comparing Figs. 18 through 21 and Figs. 30 through 33, that the efficiency of the Mod II Turbine will increase about three percent, if the radial rotor tip clearance is decreased from 0.033 inch to 0.015 inch. This increase is apparently independent of RPM, axial clearance and pressure ratio.

The most interesting finding was that the increase in efficiency with decrease in radial clearance is mostly due to a decrease in mass flow rate. That is, if all other conditions are the same, the Mod II Turbine will develop the same torque at a radial clearance of 0.015 inch as it will at 0.033 inch but at less mass flow rate. This fact is graphically portrayed by Figs. 34, 35, and 36. Figure 34 shows the referred mass flow rate as a function of stage pressure ratio for both radial clearances of 0.015 and 0.033 inch. Figures 35 and 36 are plots of referred dynamometer torque as a function of referred RPM for various stage pressure ratios at radial clearances of 0.015 and 0.033 inch, respectively. By comparing Fig. 35 with Fig. 36 it can be seen that the torque developed by the turbine is nearly independent of radial clearance. It should be noted that the pressure ratios portrayed in Fig. 35 are slightly different from those in Fig. 36. This fact must be considered on comparing the two figures since the torque developed by a turbine is very dependent on the stage pressure ratio.

Figures 37 through 40 show the experimentally determined stage efficiencies on the same plots with predicted efficiencies as a function of referred rotor RPM. The predicted values are depicted by the curves and the experimental values by the plotted points. The experimentally determined efficiencies can be seen to be from one to three percent lower than the predicted values at both radial clearances. This difference is mostly attributable to a difference in measured and predicted mass flow rates. Figures 31 and 42 are plots of the mass flow rates, and Figs. 43 and 44 are plots of the dynamometer torque. The predicted and measured torque data are generally quite closely in agreement. Likewise the predicted and measured power data, shown on Figs. 45 and 46, agree very well.

7. Description, Results and Discussion of Flow Surveys

General

Flow surveys were conducted with temperature and pressure probes before the stator, between the stator and rotor, and at the rotor discharge. The surveys were conducted to gain data from which comparisons could be made with predicted flow properties and flow properties calculated from the mean streamline analysis method presented in Section 4. In addition, the flow survey ahead of the stator was conducted to gain a measure of the validity of the basic assumptions of the mean streamline analysis.

Flow survey upstream of the stator

A number of flow surveys were made with the two Kiel probes located upstream of the stator entrance. Total temperatures and total pressures were recorded at one-tenth inch increments between the radii of 3.7 inches and 5.0 inches from the TTR axis. Figure 47 depicts the results of a typical pressure survey with the Kiel probe on the left-hand side. The total pressure can be seen to vary about 2.5 percent between the stator hub and tip radii. The same distribution of pressure was found by the survey data of the other Kiel probe. The temperature data from all traverses showed the total temperature was nearly constant at all radii. Therefore the assumption that the fluid properties at the stator entrance are uniform is not entirely satisfied.

The reason for the low total pressure at the hub radius is that the flow particles are accelerated around the hub curvature much more than the particles which follow a path at a greater radius. Since a constant loss coefficient is associated with the screens, the particle which passes the screen with the greatest velocity will incur the

greatest increase in entropy. Further, since no appreciable amount of energy is transferred in the process, all particles enter the stator at the same energy level (i.e., total temperature). However the particles near the hub are at a higher entropy level and therefore at a lower total pressure; thus, they have less energy available for the expansion across the stage.

The non-uniform pressure causes two problems with the mean streamline analysis. First, the total pressure measured ahead of the stator must be measured at such a location that it represents the pressure at the mass averaged mean streamline radius. Secondly, the loss coefficients determined by the analysis will not be exactly representative of the loss coefficients which would exist for uniform flow conditions.

The positions of the fixed total pressure probes are at very nearly the same radius as the mass flow weighted mean streamline measured at the stator exit as shown in Fig. 47. It is therefore felt that the total pressure is very nearly representative of the mean condition. A design change of the TTR to allow for flow surveys immediately upstream of the stator blades would permit the researcher to make a more quantitative analysis of the flow in this region. The one-dimensional analysis is designed to yield first-cut estimates of loss coefficients and other design parameters. Therefore, it is felt the non-uniform conditions at the stator entrance do not significantly detract from the usefulness of the calculated results.

The assumption of axisymmetric flow conditions is apparently quite valid. The differences in pressure measured by the right and left Kiel probes at any radius were less than one percent of the absolute pressure.

Further, the maximum variation in pressure indicated by the six fixed probes was always about one percent. A typical result is shown in Fig. 48.

Flow survey at the stator discharge

Pressure and temperature surveys were conducted at the exit of the stator nozzles during runs 64, 65, 66, 77, and 80. Two 5-hole flow probes built by the United Sensor Corporation, type DA 125, were used on different occasions for the pressure surveys. These probes measure yaw and pitch angle, and total and static pressure. The total pressure and yaw angle are considered exact as read. However, the static pressure must be corrected for pitch angle, Mach number, and immersion effects. Additionally, the pitch angle must be corrected for Mach number and immersion effects. Calibration curves supplied by the manufacturer are filed in the Turbo-Propulsion Laboratory Office by instrument serial numbers. Since the Mach number of the flow at the stator discharge was much larger than the Mach number at which the probes were calibrated, it was necessary to linearly extrapolate the calibration data. The temperature surveys were conducted with a locally manufactured, shielded Iron-Constantan thermocouple.

During run number 66, traverses were made at six peripheral positions from stator blade number four to blade number three. Ten data points were taken at each peripheral position. The position of each data point is shown in the plane of the stator blade trailing edges in Fig. 49. The calculated velocity distribution from the hub to the tip is shown in Fig. 50 for data points 21 through 30 and 31 through 40. These points were taken about half-way between the blades. The continuity equation was checked by

$$\dot{W} = \int_{r_h}^{r_t} 2\pi r \rho_1 V_{a_1} dr \qquad (52)$$

Equation (52) was integrated in an approximate manner by dividing the flow annulus into small increments, calculating the density and axial velocity that existed at the mean radius of each increment, and summing as

$$\dot{W} = 2\pi \sum_{r_t}^{r_h} \rho_1 V_{a_1} r \Delta r \quad ; \quad \rho_1 = \frac{P_1}{R_G T_1} \tag{53}$$

The only quantity on the right side of Eq. (52) which was neither known nor calculated from the measured flow probe data was the static temperature in the density relation. This temperature was found from the energy equation as

$$T_1 = T_{t_0} - V_1^2/2gJc_p \tag{54}$$

The results of this calculation are listed in Table V. The mass flow rate calculated from the survey data is 4.718 lb_m/sec. The mass flow rate measured by the flow nozzle reduced by the labyrinth leakage flow is 4.430 lb_m/sec. Thus the survey probe data apparently yield a mass flow rate which is about six percent too high. However, it must be kept in mind that the position of data points 21 through 30 was in the region where the flow is nearly isentropic. Therefore it can be assumed that the mass averaged axial velocities are six percent smaller than the velocities listed in Table V. This reasoning can lead to the calculation of an approximate loss coefficient as follows. The mass averaged axial velocity is found as

$$V_{a_1}^{*} = V_{a_1} \frac{\dot{W}^{*}}{\dot{W}} = 212 \frac{(4.430)}{(4.718)} = 199 \ (ft/sec) \tag{55}$$

where

V_{a1} = axial velocity from Table VI at the radius, R_m, which divides the flow channel into equal increments of mass flow.

$\dot{W}$ = flow rate from Table VI.

$\dot{W}^*$ = measured flow rate.

Then

$$V_1^* = \frac{V_{a_1}^*}{\cos\alpha_1} = \frac{199}{\cos 70.1^\circ} = 585\,(\text{ft/sec}) \tag{56}$$

where

V_1^* = mass averaged stator exit velocity

α_1 = measured stator exit angle at radius, R_m.

The stator loss coefficient can now be calculated as

$$\zeta_s = 1 - \frac{V_1^{*2}/2gJc_p}{T_{t_o}\left[1-\left(P_1/P_{t_o}\right)^{\gamma-1/\gamma}\right]} = 1 - \frac{585^2/2(32.17)778.16}{576.73\left[1-\left(17.1/20.57\right)^{.286}\right].024} = \underline{\underline{0.061}} \tag{57}$$

where

p_1 = static pressure measured by the flow probe at R_m

P_{t_o} = mean total pressure at the stator entrance

T_{t_o} = total temperature measured at the stator entrance.

The temperature surveys at the stator exit indicated that the total temperature was very nearly constant at all radii.

The results of the survey data are graphically compared to the predicted results on Figs. 55 and 56. The absolute exit angles, α_1, coincide very closely with the exit angles computed in the mean streamline analysis. However, the mean velocities from the mean streamline analysis were consistently higher than the measured velocities.

Flow survey at the rotor discharge

Pressure and temperature surveys were conducted at the rotor discharge during run numbers 67 and 76. During run number 67 the total inlet temperature, T_{t_o}, total pressure, P_{t_o}, and the RPM were set to the same values as used in the traverse at the stator exit conducted during run 66. Therefore, the results from run 67 can be used with the results of run 66 to determine the actual velocity triangles at any blade radius. Similarly the inlet conditions of run 76 match run 75. The power developed by the machine can then be determined and compared to the power measured. Likewise, other performance variables can be computed and compared with the results of the mean streamline analysis and the predicted values.

Figure 52 shows the velocity distribution at the rotor exit, measured during run 67, and computed by the method described previously for the DA-125 type probe. On the other hand, Fig. 53 shows the velocity distribution computed with the following assumptions:

1. The total pressure, P_{t_2}, and total temperature, T_{t_2}, are assumed correct as measured by the probes.
2. The static pressure, p_2, is taken as the atmospheric barometric pressure.
3. The static temperature is then computed from

$$T_2 = T_{t_2} \left({}^{p_2}/_{p_{t_2}} \right)^{\gamma-1/\gamma} \tag{58}$$

4. The velocity is computed as

$$V_2 = \left[2gJc_p \left(T_{t_2} - T_2 \right) \right]^{1/2}$$

It is felt this method of data reduction is more accurate than the method which uses the probe calibration curves supplied by the vendor. Since immersion effects on static pressure measurements can be quite large, and are not taken into account, the calibration curves cannot be considered exact.

Since the absolute rotor exit angle, α_1 has been measured, the axial and peripheral velocity components may be computed from

$$V_{a_2} = V_2 \cos \alpha_2 \tag{59}$$

and

$$V_{u_2} = V_2 \sin \alpha_2 \tag{60}$$

Also, the relative velocity components are obtained from

$$W_{a_2} = V_{a_2} \tag{61}$$

and

$$W_{u_2} = V_{u_2} - U_2 \tag{62}$$

Then, the relative discharge flow angle is

$$\beta_2 = \tan^{-1} \frac{W_{u_2}}{W_{a_2}} \tag{63}$$

Table VI lists the results of run 67. The mass flow rate was computed as

$$\dot{W} = \sum_{r_h}^{r_t} 2\pi r \rho_2 V_{a_2} \Delta r \tag{64}$$

Because of the shape of the pressure probe, data points could be taken only at greater distances from the shroud than 0.16 inch. This condition made it necessary to assume the velocity distribution between the shroud and the measuring stations closest to it. Similar to the assumption used to develop Eq. (89), Appendix I, the axial

velocity distribution was considered to be linear from zero at the shroud to the nearest measured velocity. With this assumption, the mass flow rate was determined to be 4.42 lb_m/sec. This value coincides closely with the mass flow rate of 4.41 lb_m/sec measured by the flow nozzle.

The radius which divides the mass flow into two equal parts was found to be 4.361 inches. By comparison, the root mean square radius used in the computer program for the rotor is 4.187 inches. This difference causes the derived peripheral velocity from Eq. (24) to be in error by about six percent. Therefore, all quantities calculated by Eqs. (25) through (33) will be in error also. Because of this discrepancy, the rotor exit velocities, flow angles, and loss coefficients obtained by the mean streamline analysis method should be considered only as approximations of the actual values.

The power produced by each increment of rotor area was computed from

$$\Delta HP = \frac{\Delta \dot{W}}{550g} U(V_{u_1} - V_{u_2}) \tag{65}$$

The formulas for calculating the variables in Eq. (65) are listed in Table VI.

From a summation of these increments, the total power developed by the rotor was determined to be 63.3 horsepower. The power calculated by Eq. (38) from the measured dynamometer torque and the RPM was 62.1 HP for the data from run 66 and 63.1 HP for the data from run 67.

The results of the flow survey from run 67 are compared to the predicted results given by Harrison[7], on Figs. 55 and 56. It is felt that the discrepancy between predicted and measured exit angles is

[7]Harrison, loc. cit.

caused by the separated flow regions in the rotor which were not taken into account in the prediction method. In Fig. 5 dark areas can be seen at the tip and hub of the rotor blades. These areas consist of oil and dust which accumulated on the blades during the runs because of separations at these locations. Also in Fig. 57 dark areas can be seen along the blade near the hub, as well as dark lines that point radially outward. Apparently thick boundary layers or separated flow regions exist in these areas. The dark lines are probably caused by dust particles being thrown outward by centrifugal forces.

8. Recommendations

The following recommendations are not presented as original thoughts of the author, but rather as a listing of the logical steps which should be undertaken as a continuation of this study.

1. Blade shapes geometrically similar to the Mod II blading should be tested in the Rectilinear Cascade Test Rig of the Naval Postgraduate School. The loss coefficients found in the present study could be validated and the interesting changes of the pressure distribution with axial clearance could be investigated.

2. The non-steady flow conditions caused by the rotor passing through blade wakes of the stator should be examined in greater detail. The wake patterns could be measured by hot wire anemometers now available. The change of the pressure distribution with axial clearance may be related to non-steady flow phenomena.

3. The TTR should be modified to obtain more uniform flow conditions at the stator entrance. A fix that should be attempted is to remove the turbulence reduction screens and to insert an outer wall

contour in the channel leading to the stator entrance. If this change is unsuccessful in reducing turbulence and increasing uniformity, then the TTR stator assembly should be fitted with a larger diameter inlet pipe. Also, it would be very useful to have the capability of conducting a flow survey immediately upstream of the stator entrance.

4. Further performance tests should be conducted on the Mod II Turbine. Particularly, tests at higher head coefficients should be performed after the water brake dynamometer becomes available. It may be determined that the relationship between efficiency and axial clearance is a function of head coefficient.

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TABLE I

MOD II TURBINE DESIGN PARAMETERS

ITEM	SYMBOL	UNITS	STATOR	ROTOR
Number of Blades	z		19	18
Blade Height	h	in.	1.435	1.618
Hub Radius	r_h	in.	3.398	3.300
Mean Radius	r_m	in.	4.188	4.188
Tip Radius	r_t	in.	4.851	4.918
Throat Diameter	a	in.	0.4635	0.5400
Throat Area	A_{th}	$in.^2$	12.705	15.610
Axial Exit Area	A_{ax}	$in.^2$	37.65	41.77
Exit Angle	α	deg.	68	0
Relative Exit Angle	β	deg.	9.2	-66.4
Loss Coefficient	ζ		0.079	0.093
Blockage Factor	ξ		0.970	0.965
Isentropic Head Coef.	K_{is}		2.56	
Work Coefficient	K_w		2.14	
Theoretical Degree of Reaction	r^*		0.435	
Efficiency (Total to Static)	η	o/o	83.80	
Rotational Speed	N	RPM	14,200	
Stage Pressure Ratio	P_{to}/P_2		1.484	

TABLE II

MEASURED DATA FOR TURBINE PERFORMANCE TESTS

TRANSONIC TURBINE TEST RIG

Desired Quantity	Measured Item	Measured Units	Symbol	Computer Character
1. FLOW RATE				
	Flow nozzle total pressure	in. Hg.	P_{tn}	PNDZ
	Flow nozzle total temperature	millivolts	T_{tn}	TNDZ
	Pressure differential across flow nozzle	in. H_2O	h_n	DH
	Turbine plenum total pressure	in. Hg.	P_{2p}	PSPL
2. STATOR ENTRANCE PROPERTIES				
	Stator entrance total pressure	in. Hg.	P_{to}	PTPL
	Stator entrance total temperature	millivolts	T_{to}	TTPL
3. STATOR DISCHARGE PROPERTIES				
	Stator tip static pressure	in. Hg.	P_t	PTIP
	Stator hub static pressure	in. Hg.	P_L	PHUB
	Force exerted on stator assembly by the axial force capsule	counts	F_s	FAX
	Moment exerted on stator assembly by the stator torque capsule	counts	M_s	TORQ
	Static pressures at the end of the shroud	in. Hg.	$P_{15}, P_{16}, P_{17}, P_{18}, P_{19}, P_{20}$	P15-P20
	Axial force exerted on the stator assembly by the closure plate	counts	F_{CL}	CLFAX
	Moment exerted on the stator assembly by the closure plate	counts	M_{CL}	CLTRQ
4. ROTOR DISCHARGE PROPERTIES				
	Static pressure in the test hood	in. Hg.	P_{hd}	PHD
	Dynamometer torque	counts	M_D	DYNAR
	Rotor rotational speed	RPM	N	RPM

TABLE III

MOD II TURBINE TEST RUNS 1967

JAN.-AUG.

Run No.	Δr (in.)	Δx (in.)	P_{to}/P_2 (approximate)	N (RPM x 10^{-3})	Test Purpose
o 51	0.033	0.410	1.4,1.5	13-20	+
* 52		0.620	1.4,1.5	14	-
* 53		0.620	1.3,1.4,1.5	11-18	+
* 54		0.410	1.6,1.8	15-18	+
o 55		0.410		0	1
* 56		0.410	1.4	13-19	1
* 57		0.410	1.4	13-19	2
* 58		0.620	1.3,1.5,1.6	10-17	+
* 59		1.000	1.3,1.4,1.5,1.6	10-17	+
* 60		0.200	1.3,1.4,1.5,1.6	10-17	+
* 61		0.410	1.3,1.4	11-17	+
* 62		0.410.	1.5,1.6	13-17	+
* 63		1.500	1.3,1.4,1.45,1.5,1.6	11-19	+
o 64	0.015	1.000	1.4	14.6	3
o 65			1.4	14.6	3
o 66			1.4	14.6	3
o 67			1.4	14.6	4
* 68			1.3,1.4,1.5,1.6	11-18	+
* 69		0.410	1.3,1.4,1.5	11-19	+
* 70		0.410	1.6	14-19	+
* 71		0.200	1.3,1.4	11-17	+
* 72		0.410	1.3,1.4,1.5	11-18	+
* 73		0.200	1.3,1.5		+
o 74		0.200	1.3,1.4		+
o 75		0.410	1.3	11-5	3
o 76		0.410	1.3,1.4,1.5	11-19	4
o 77		0.410 & 1.000	1.3,1.4	11-19	+
o 78		.200,.410,1.000	1.3	11-18	2
* 79		.200	1.3,1.4	11-17	+
o 80		.410	1.3	10-17	+

o = without exhauster
* = with exhauster
+ = performance characteristics
- = hood check

$P_2 = P_{Barometer}$

$P_2 < P_{Barometer}$

1 = Dynamometer check
2 = Spring capsule dyna.
3 = Stator exit survey
4 = Rotor exit survey

TABLE IV

CHRONOLOGICAL RECORD OF MOD II TURBINE TESTS 1967

Run No.	Date	Duration (Hrs)	Remarks
51	1-26	3.5	Dynamometer arm slipped, put set screw in arm
52	2-3	2.5	Tested hood for leaks, tested dynamometer
	2-9		Tested waterbrake, slight bearing problem
53	4-3	3.0	Dyna. capsule 25 counts off at shut down
54	4-24	5.25	P_{t0}/P_2 = 1.6 & 1.8, dyna. capsule off 30 counts
55	4-25		Checked dyna. capsule at various temperatures by heating with a lamp. - very temp. sensitive -50 to +170 counts
			Installed constant temp. environment system around dynamometer capsule
56	5-11	3.0	Performance test at P_{t0}/P_2 = 1.4 with dyna. capsule; took tare readings during run. Dyna. checked good at shut-down
57	5-16	2.5	Used spring capsule to check dyna. readings obtained during run 56 - satisfactory
58	5-31	6.0	Good data - no apparent problems
59	6-1	6.0	" " " " "
60	6-5	5.5	" " " " "
61	6-7	3.0	" " " " "
62	6-9	4.0	" " " " "
63	6-13	5.0	" " " " "
	6-14 to 6-21		Replaced shroud with new shroud; Δr = 0.015 in.; cleaned all probes & lines with high press. N_2. Unable to calibrate closure plate axial force device. Designed new device & assembled mach w/o closure plate instrumentation
64	6-23	6.5	Temp. & press. traverse at stator exit. Y.C. DA125 S/N 926
65	6-26	3.5	" " " " " " "
66	6-27	5.5	60 data point pressure traverse at stator exit with DA125 S/N 926, 10 data points with S/N 928 for comparison.
67	6-28	5.0	Temp. & press. traverse at rotor discharge. Y.C. D.A. 125, S/N 926. Two peripheral positions checked about 30° apart.-readings less than ± 0.25 cm. H_2O difference

68	7-5	6.5	Good performance data - no apparent problems
69-76	7-10 to 8-5	44.0	All dyna. readings during these runs are possibly in error. Set screw had worn a grove in the shaft causing slippage. Discovered during run #77. Also A.C. compressor very unstable.
	7-20		Installed new closure plate axial force flexture. Calibrates good.
75	7-31		Traverse before stator with left & right Kiel probe. Transverse aft of stator with S/N 928.
76			Traverse aft of rotor with S/N 928
77			Discovered torque arm movement during run - made calibration of movements.
78			Spring capsule dynamometer used
79			Checked capsule calibrations
80			Traverse aft of stator with S/N 928

TABLE V

STATOR DISCHARGE FLOW SURVEY RUN NUMBER SIXTY-SIX

Data Point	radius r (in.)	Velocity V_1 (ft/sec)	Absolute Angle α_1 (deg.)	Static Press. P_s (psia)	Static Temp. T_1 (°R)	Δr (in.)	Va_1 1	Vu_1 2	$\Delta\dot{W}$ 3	V^* 4	U 5	Wu_1 6	W_1 7	β_1 8
21	4.71	543	68.9	17.93	553	0.225	196	500	0.7913	510	502	-2	196	0
22	4.56	564	69.2	17.71	551	0.150	200	516	0.5185	530	487	29	202	8.3
23	4.41	583	69.9	17.47	549	0.150	200	539	0.4960	548	471	68	211	18.8
24	4.26	611	70.1	17.21	546	0.150	210	568	0.4982	575	454	114	239	28.5
25	4.11	632	70.2	16.96	544	0.150	214	587	0.4847	594	438	125	248	30.3
26	3.96	655	70.4	16.69	541	0.150	221	612	0.4769	616	422	190	292	40.6
27	3.81	679	70.8	16.43	538	0.150	219	637	0.4501	638	406	231	337	46.6
28	3.66	705	70.4	16.17	535	0.150	238	662	0.4652	662	390	272	411	48.6
29	3.51	729	70.2	15.93	532	0.150	247	686	0.4586	685	374	312	501	51.6
30	3.42	726	71.2	15.87	582	0.028	234	688	0.0786	683	365	323	551	54.1

1 $Va_1 = V_1 \cos \alpha_1$ (ft/sec)

2 $Vu_1 = V \sin \alpha_1$ (ft/sec)

3 $\Delta\dot{W} = 2\pi r \Delta r (P_s/R_G T_1) Va_1$ (lb_m/sec)

4 $V^* = \dfrac{\dot{W} V}{\Sigma \Delta\dot{W}}$ (ft/sec)

$\dot{W}$ = measured flow rate (lb_m/sec)

= 4.4 (lb_m/sec)

5 $U = N\pi r/(360)(12)$(ft/sec)

6 $Wu_1 = Vu_1 - U$ (ft/sec)

7 $W_1 = (W_{u_1}^{\ 2} + W_{a_1}^{\ 2})^{\frac{1}{2}}$ (ft/sec)

where $Wa_1 = V_{a_1}$

8 $\beta_1 = \mathrm{Tan}^{-1} \left(\dfrac{Wu_1}{Wa_1} \right)$

TABLE VI

ROTOR DISCHARGE FLOW SURVEY RUN NUMBER SIXTY-SEVEN RESULTS

Data Point	*radius r_2 (in.)	Δr (in.)	P_{T_2} (cm H_2O)	P_2/P_{T_2}	T_2/T_{t_2} 1	V_2 2	α_2	V_{a_2} 3	$\Delta\dot{W}$ 4	V_{u_2} 5	V_{u_1} 6	U_2 7	ΔHP 8
15	4.773	0.0925	1084.1	.9567	.9874	284.9	20.3	267	0.383	97	498	610	4.899
16	4.723	0.025	1085.4	.9555	.9871	288.2	21.8	268	0.103	107	500	604	1.274
1	4.673	0.1	1090.9	.9507	.98561	304.4	22.6	282	0.428	117	505	597	5.186
2	4.573	0.1	1095.9	.9463	.9843	318.0	22.5	294	0.437	122	515	584	5.161
3	4.473	0.1	1096.3	.9460	.9842	319.0	22.4	295	0.429	122	526	572	5.183
4	4.373	0.1	1093.1	.9488	.9851	309.8	22.3	286	0.406	117	540	559	5.045
5	4.273	0.1	1084.5	.9563	.9873	286.0	21.0	267	0.371	103	560	546	4.874
6	4.173	0.1	1078.3	.9618	.9889	267.4	20.2	251	0.340	92	570	533	4.593
7	4.073	0.1	1076.8	.9631	.9893	262.5	19.0	248	0.328	85	585	521	4.542
8	3.973	0.1	1072.1	.9674	.9905	247.4	18.6	234	0.302	79	600	508	4.259
9	3.873	0.1	1064.5	.9743	.9925	219.8	18.2	208	0.262	68	620	495	3.785
10	3.773	0.1	1055.8	.9823	.9949	181.2	16.4	174	0.213	51	635	482	3.190
11	3.673	0.1	1045.9	.9916	.9976	124.3	13.3	121	0.144	29	648	469	2.235
12	3.573	0.1	1043.5	.9939	.99825	106.2	9.6	105	0.122	18	670	457	1.927
13	3.473	0.1	1042.3	.9950	.99862	94.3	11.6	92.5	0.104	19	680	444	1.626
14	3.373	0.05	1043.2	.9942	.99834	103.4	1.0	103.4	0.057	2	660	431	0.852

1 $T_2/T_{t_2} = (P_2/P_{t_2})^{0.286}$

2 $V_2 = \left[(2)(32.17)(778.16)(0.24)(T_{t_2} - T^2)\right]^{1/2}$

3 $V_{a_2} = V_2 \cos\alpha_2$

4 $\Delta\dot{W} = 2\pi r \Delta r \,(P_2/R_0 T_2)\, V_{a_2}$

5 $V_{u_2} = V_2 \sin\alpha_2$

6 $V_{u_1} \Rightarrow$ Run # 66 PLOTTED VALUES

$\Sigma\dot{W} = 4.42\ lb_m/sec$

$\Sigma\Delta HP = 63.26$ Horsepower

7 $U_2 = N\pi r_2/12(360)$

8 $\Delta HP = \dfrac{\Delta\dot{W}\, U (V_{u_1} - V_{u_2})}{(32.17)(550)}$

N = 14,645 RPM

$P_2 = P_{Bar} = 30.10$ in.Hg.

$T_{t_2} = 576.73^{o}R$

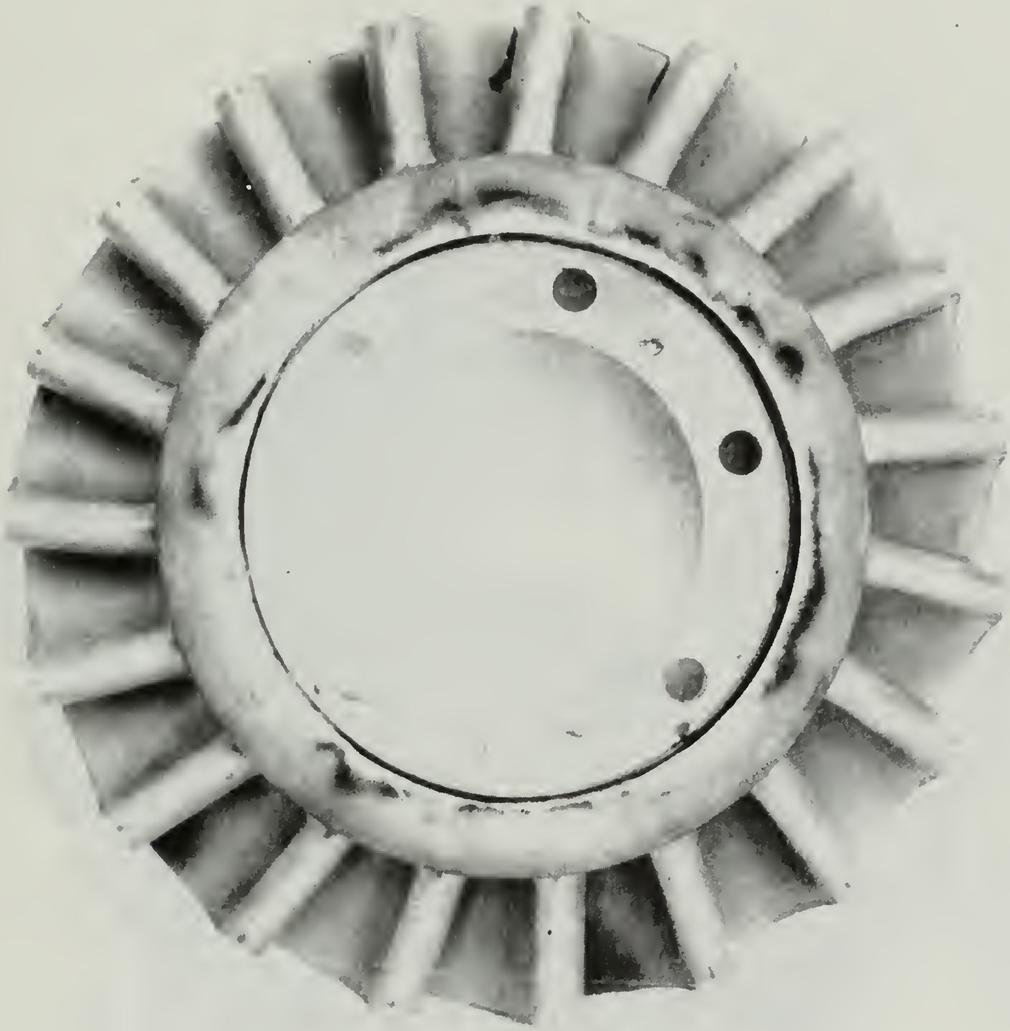


FIGURE 1

MOD II TURBINE STATOR (After tests)

(View showing stator entrance)

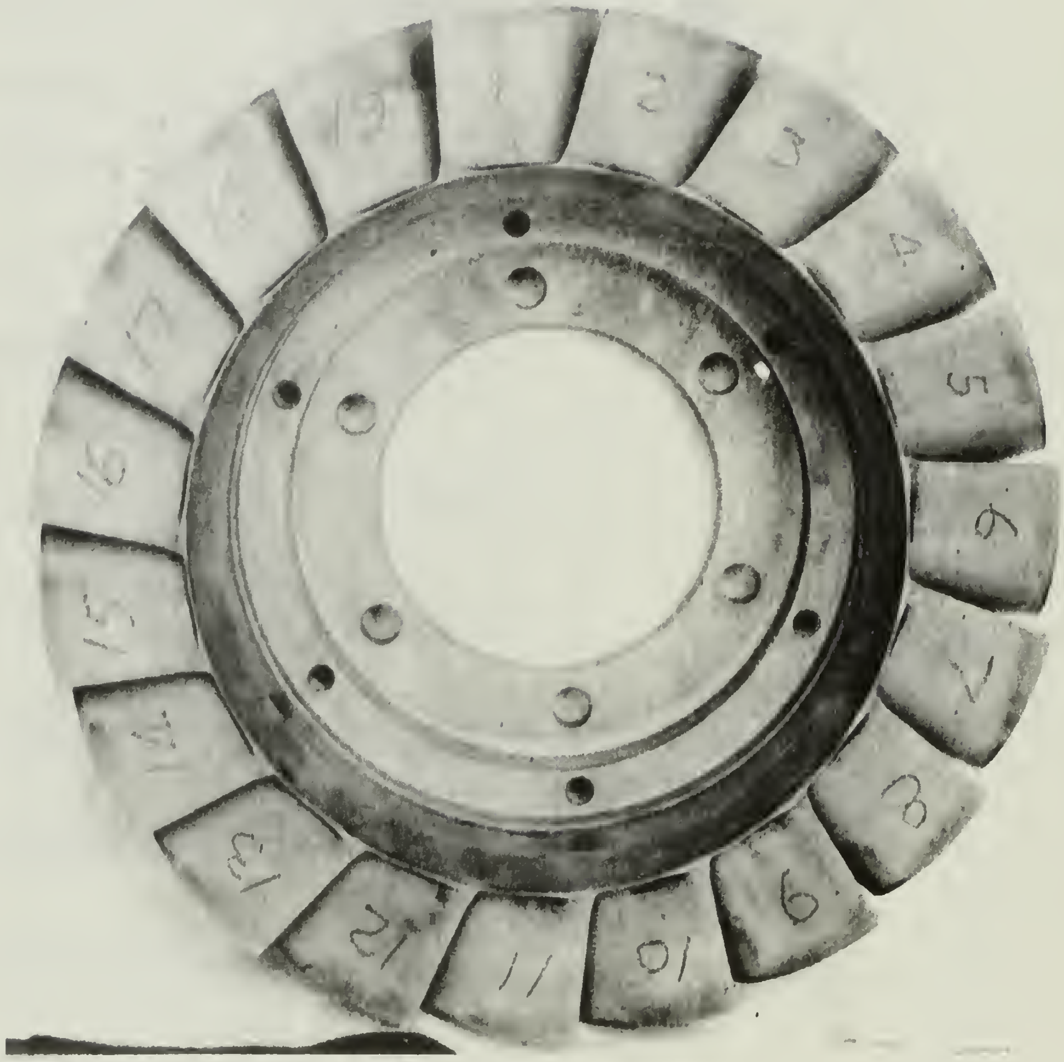


FIGURE 2

[illegible] TURBINE STATOR (after test)

(View showing stator exit)

FIGURE 3

MOD II TURBINE STATOR (After tests)

(View showing blade profiles)

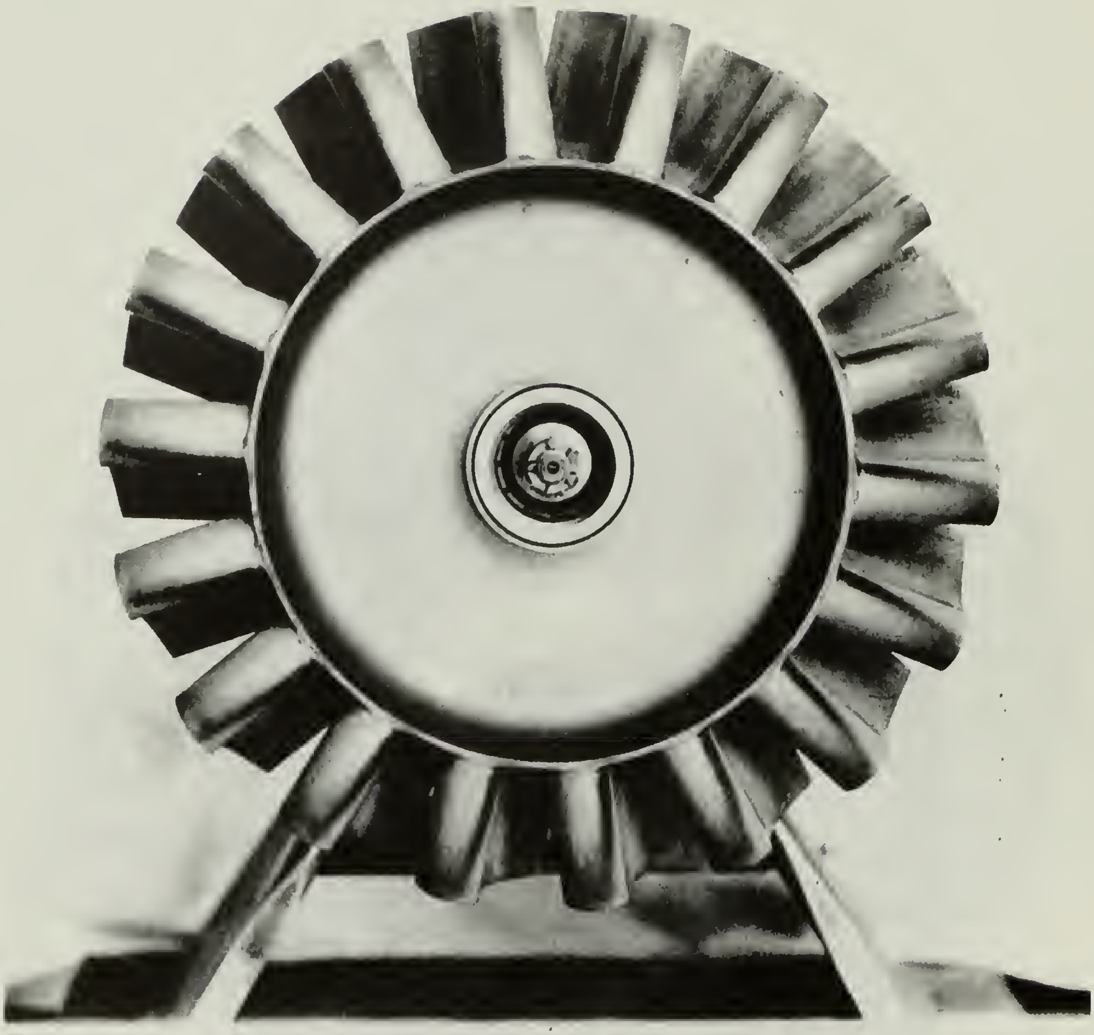


FIGURE 4

[illegible] TURBINE ROTOR (After tests)

(View showing rotor entrance)

FIGURE 5

MOD II TURBINE ROTOR (After tests)

(View showing rotor exit)

FIGURE 6

MOD II TURBINE (After tests)

(View showing blade profiles)

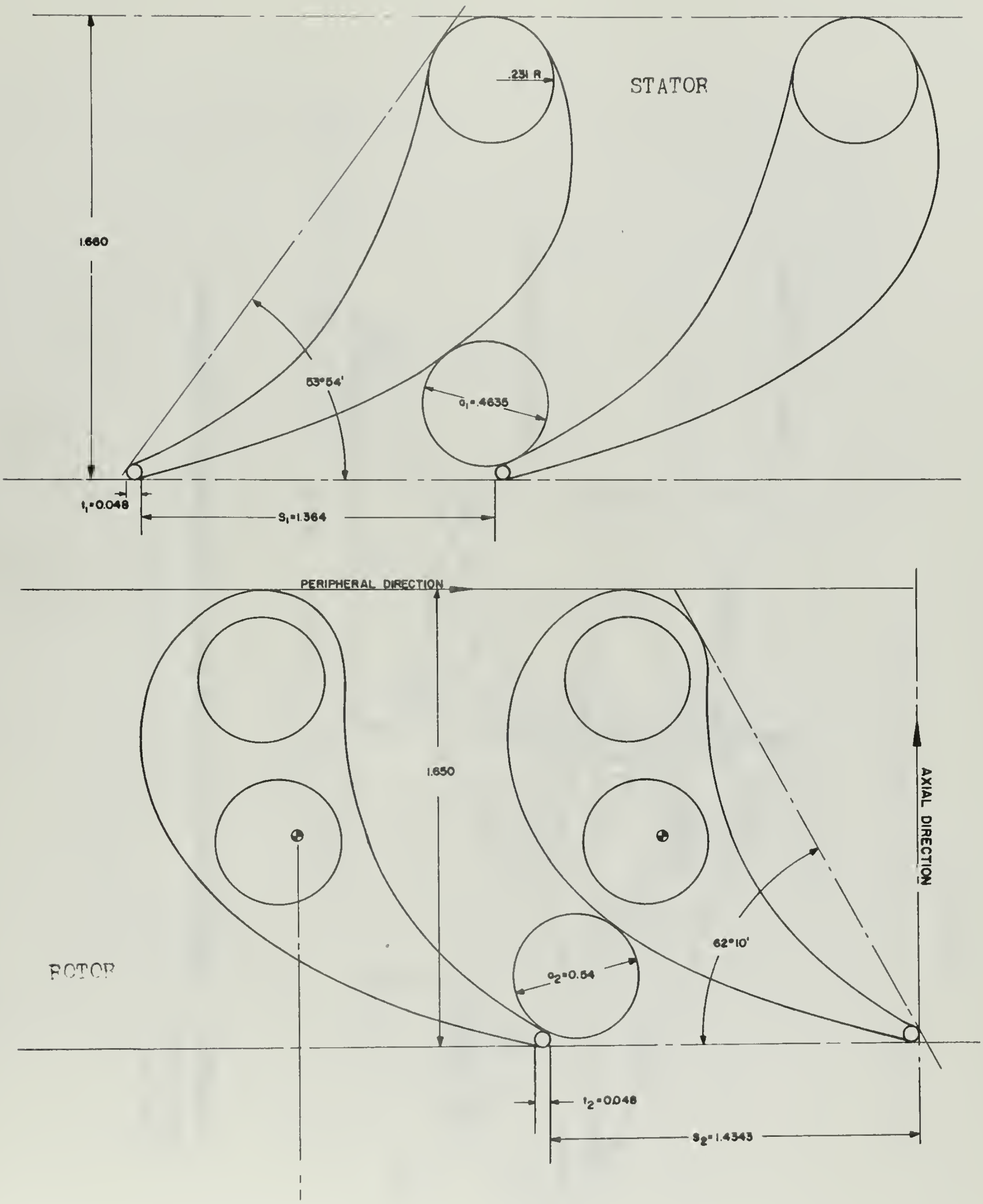


FIGURE 7

MOD II TURBINE BLADE PROFILES

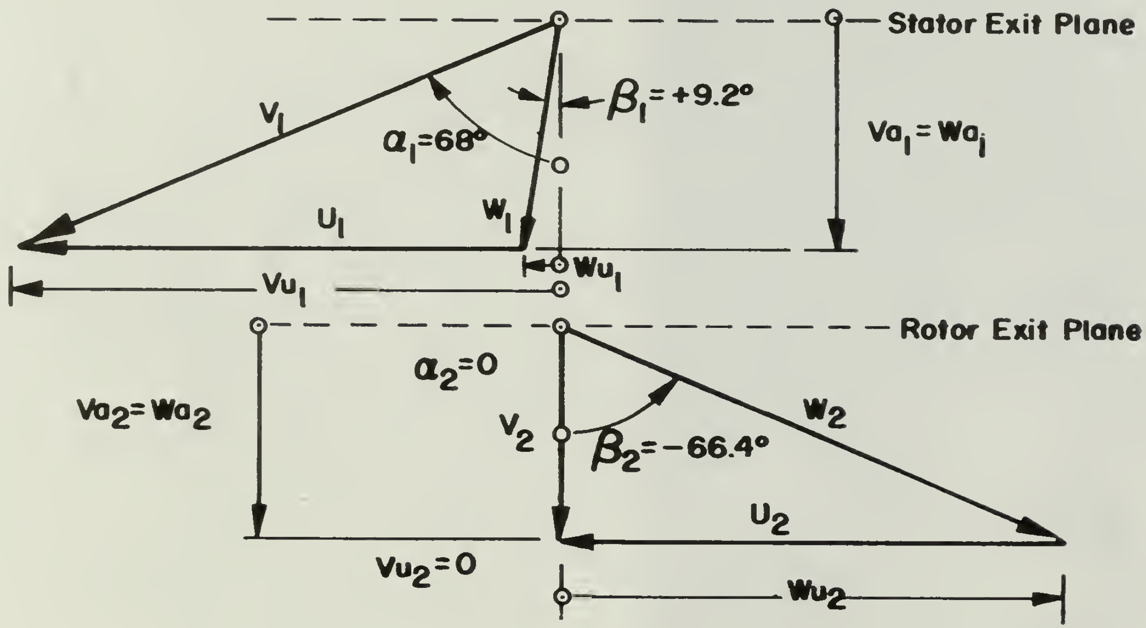
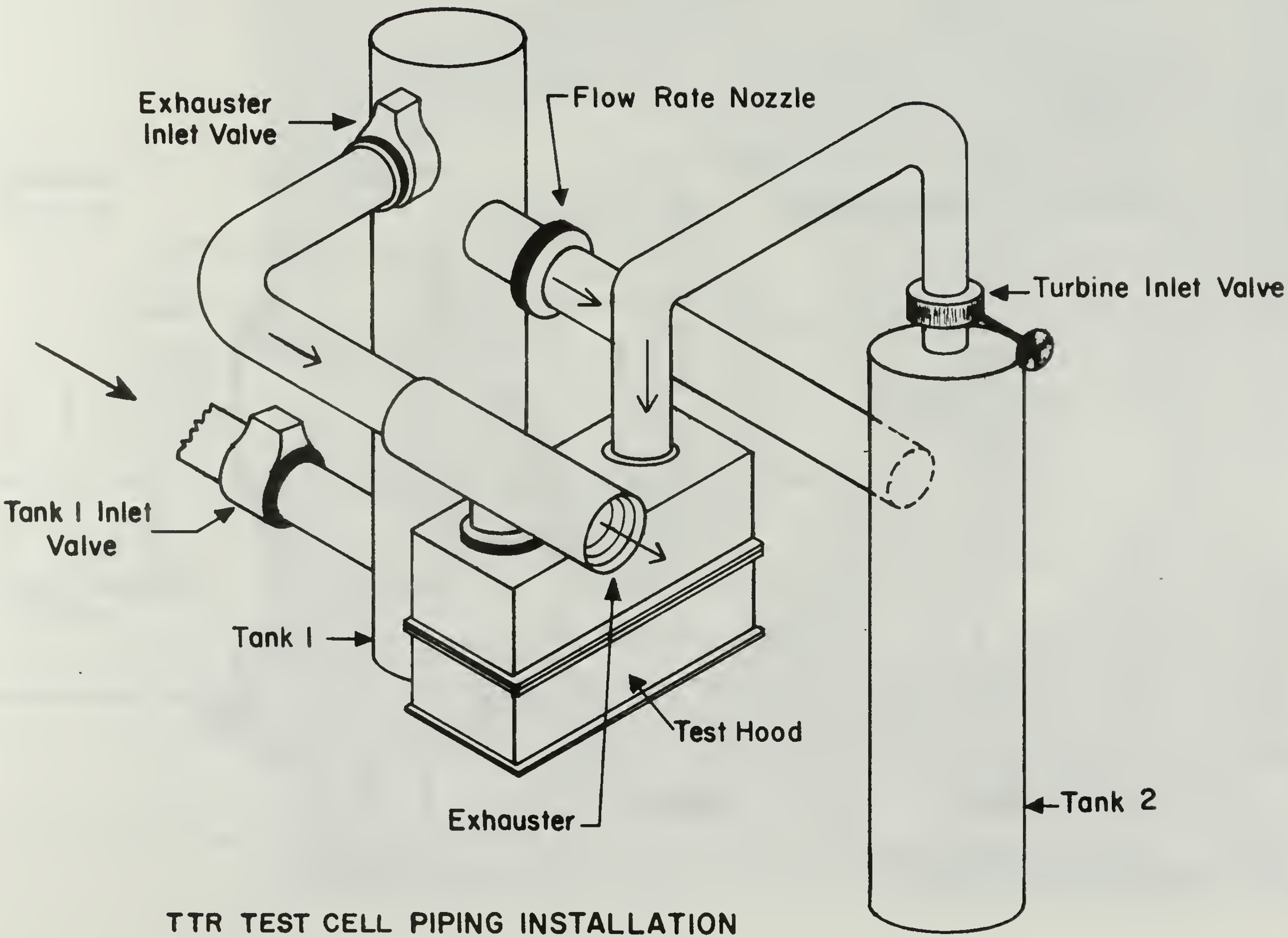


FIGURE 8 MEAN STREAMLINE, DESIGN POINT, Velocity DIAGRAM



TTR TEST CELL PIPING INSTALLATION

FIGURE 9

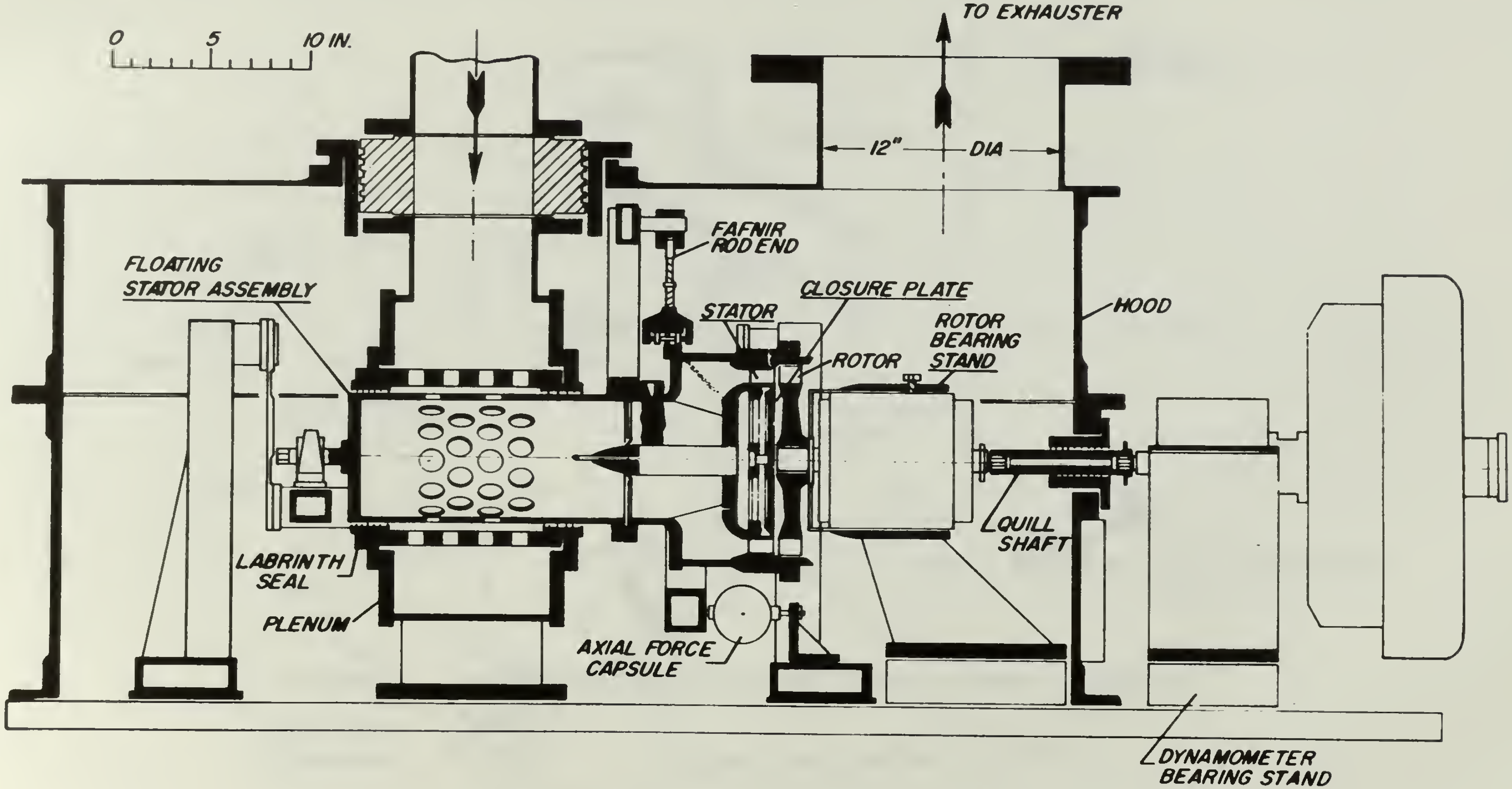


FIGURE 10

TRANSONIC TURBINE TEST RIG

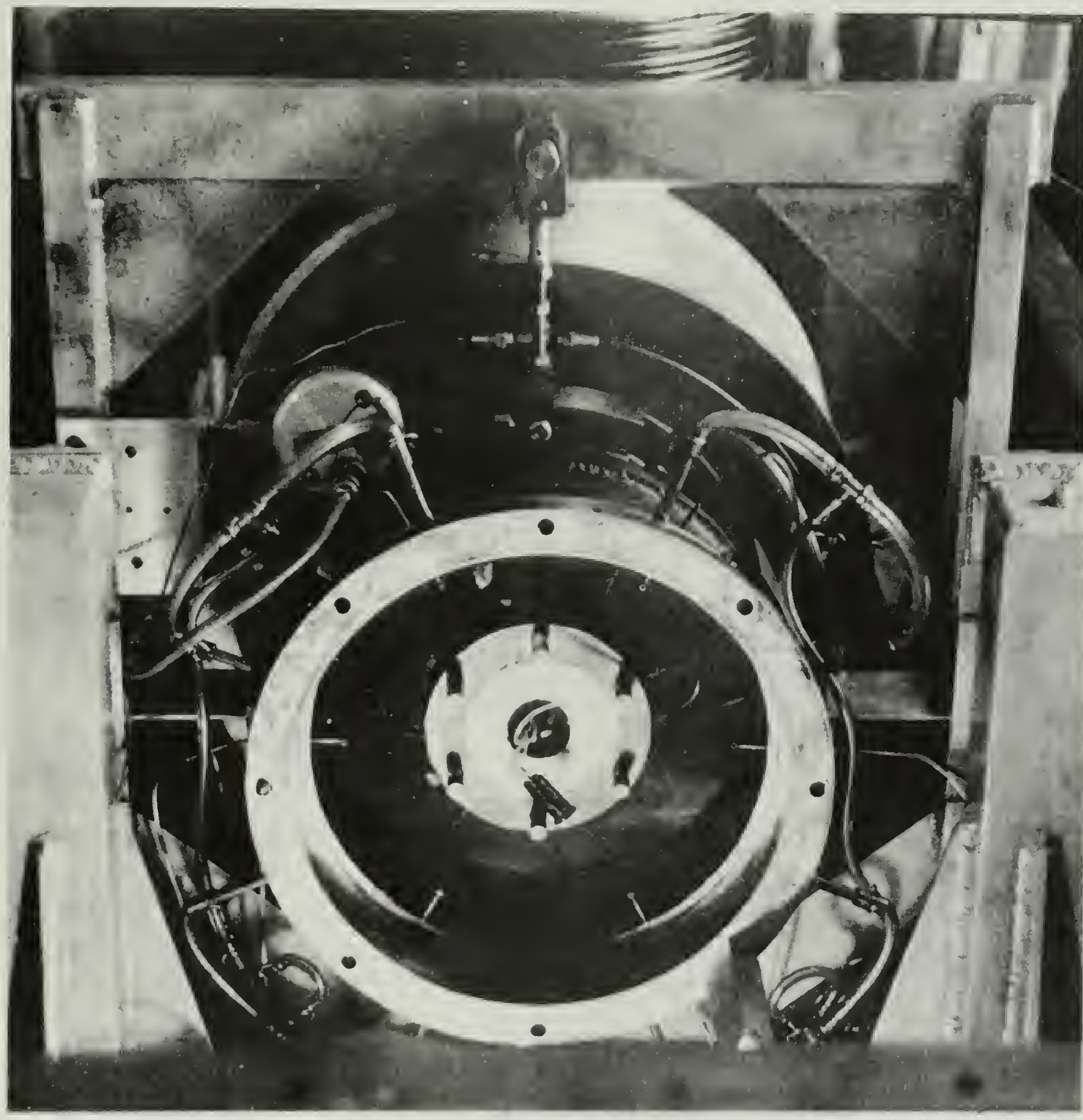


FIGURE 11

TRANSONIC TURBINE TEST RIG

(View showing turbulence reduction screens with stator and rotor removed)

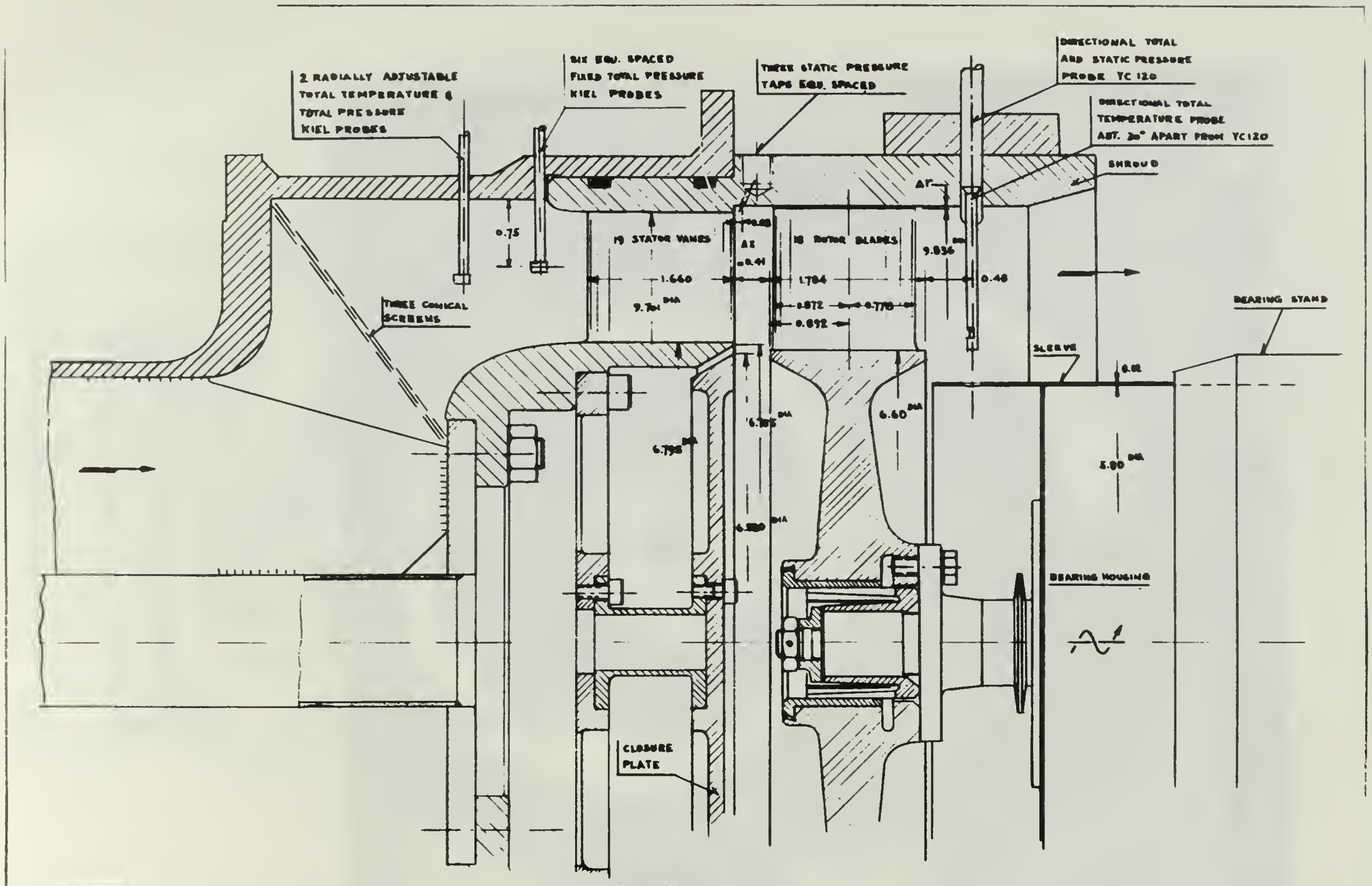


FIGURE 12

ARRANGEMENT OF MOD II TURBINE BLADING IN TEST RIG

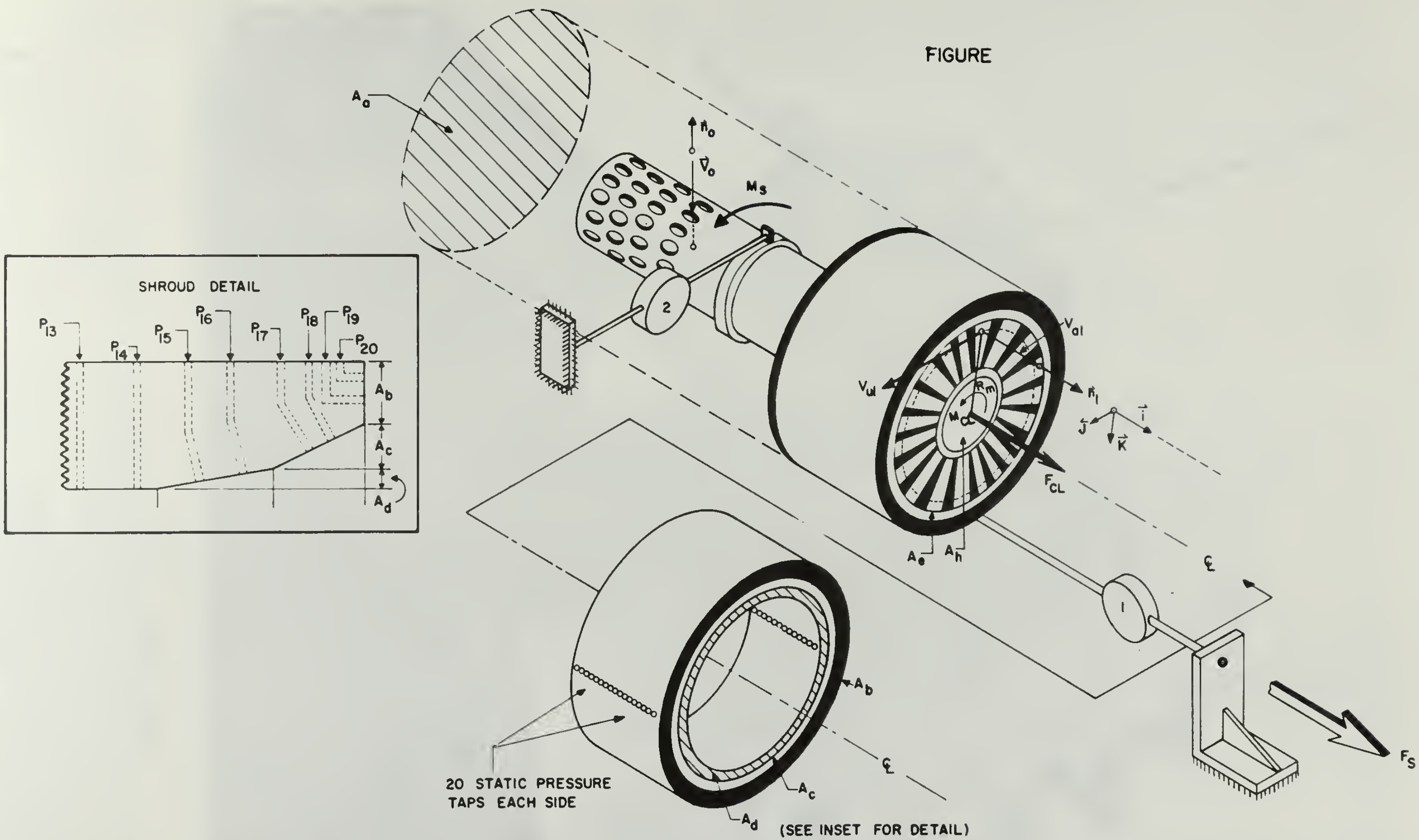


FIGURE 13

TTR STATOR ASSEMBLY AND SHROUD

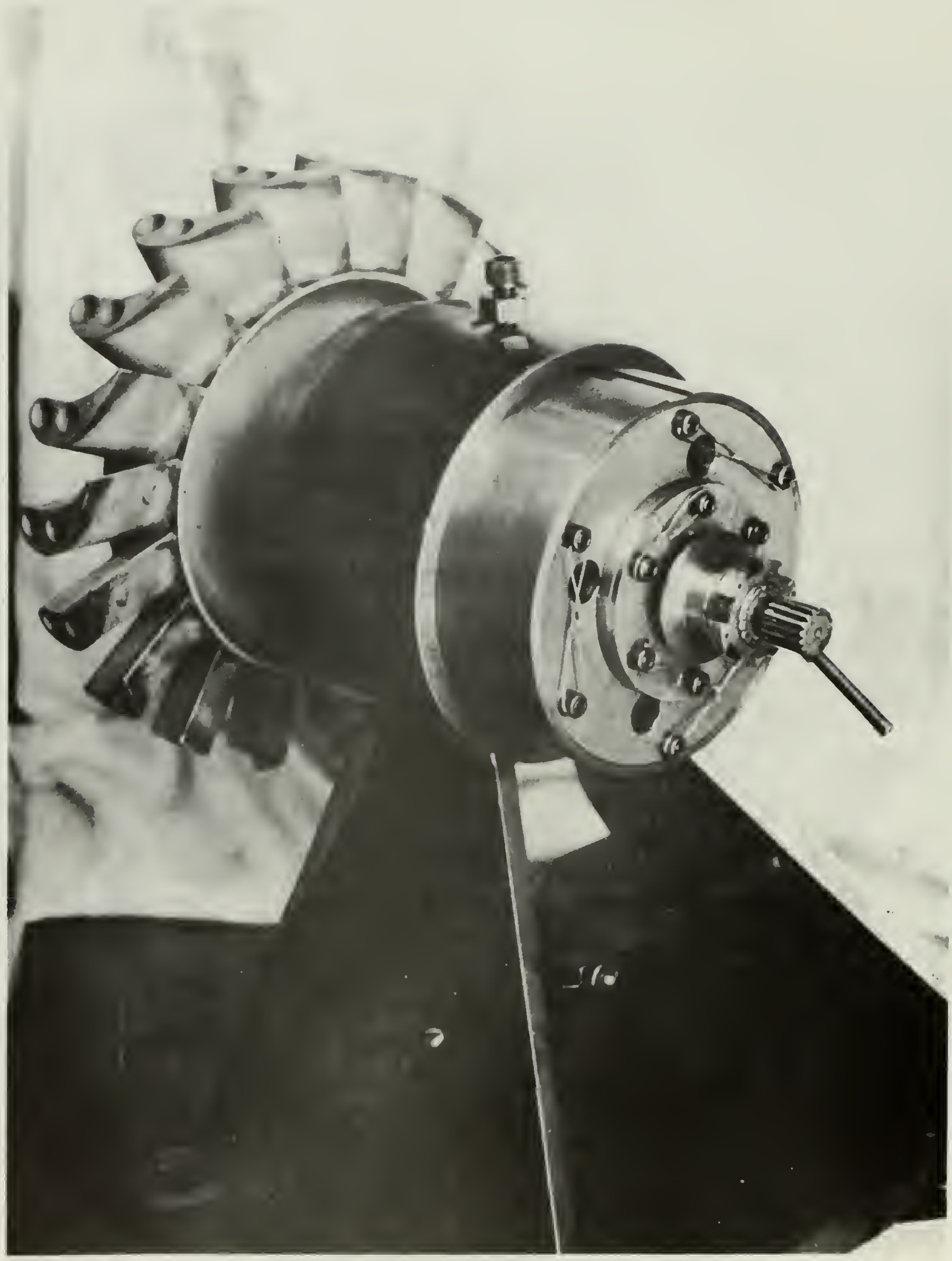


FIGURE 14

ROTOR BEARING SUPPORT ASSEMBLY AND MOD I TURBINE ROTOR

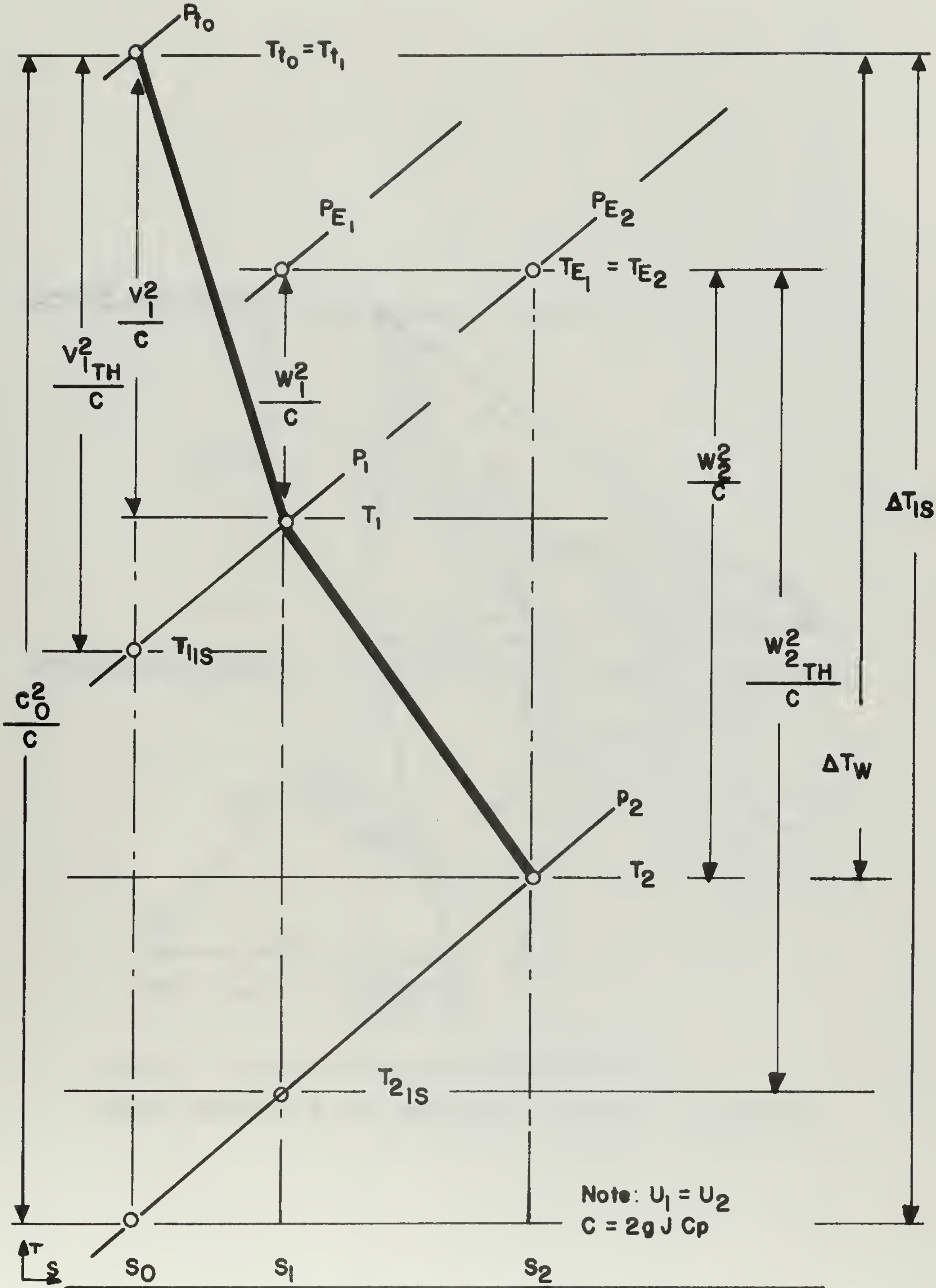


FIGURE 15 THERMODYNAMIC PROCESS OF FLUID IN AN AXIAL TURBINE STAGE

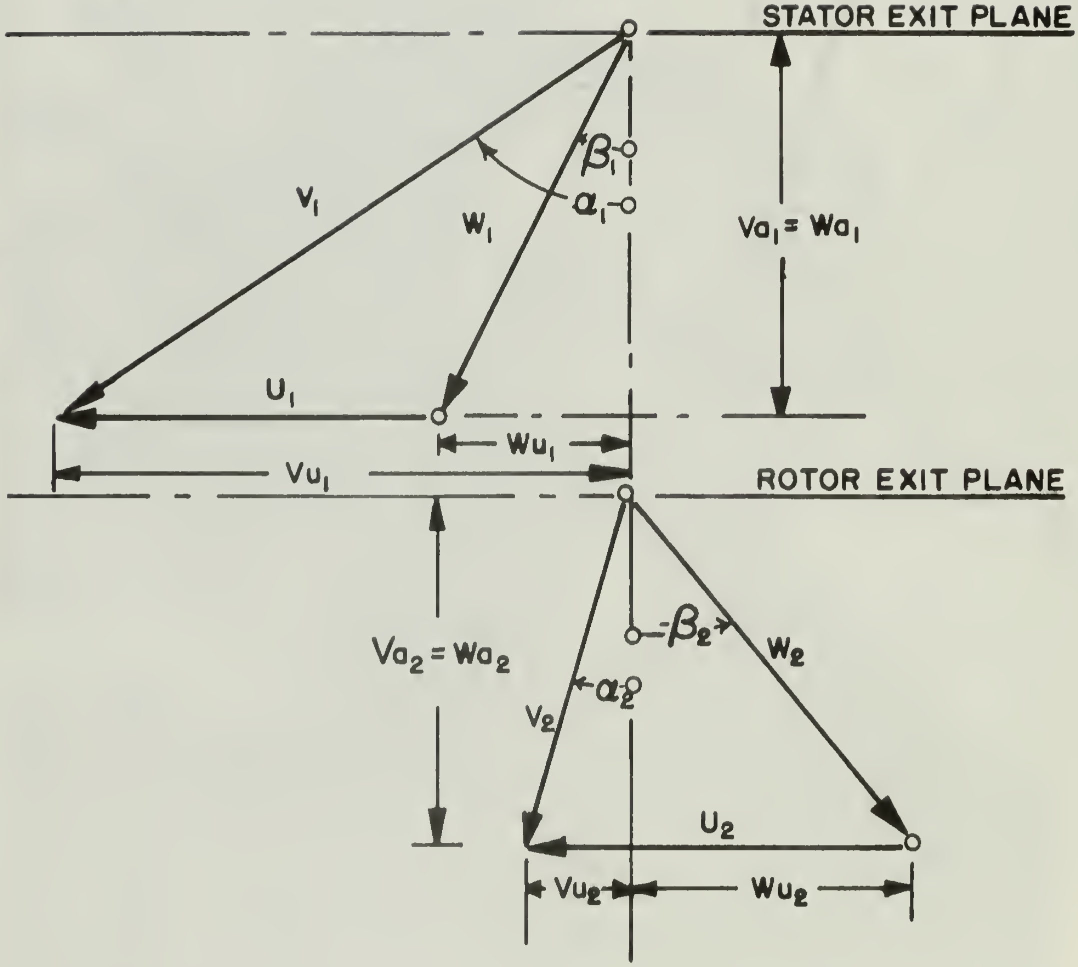


FIGURE 16 VELOCITY DIAGRAM OF A TURBINE STAGE

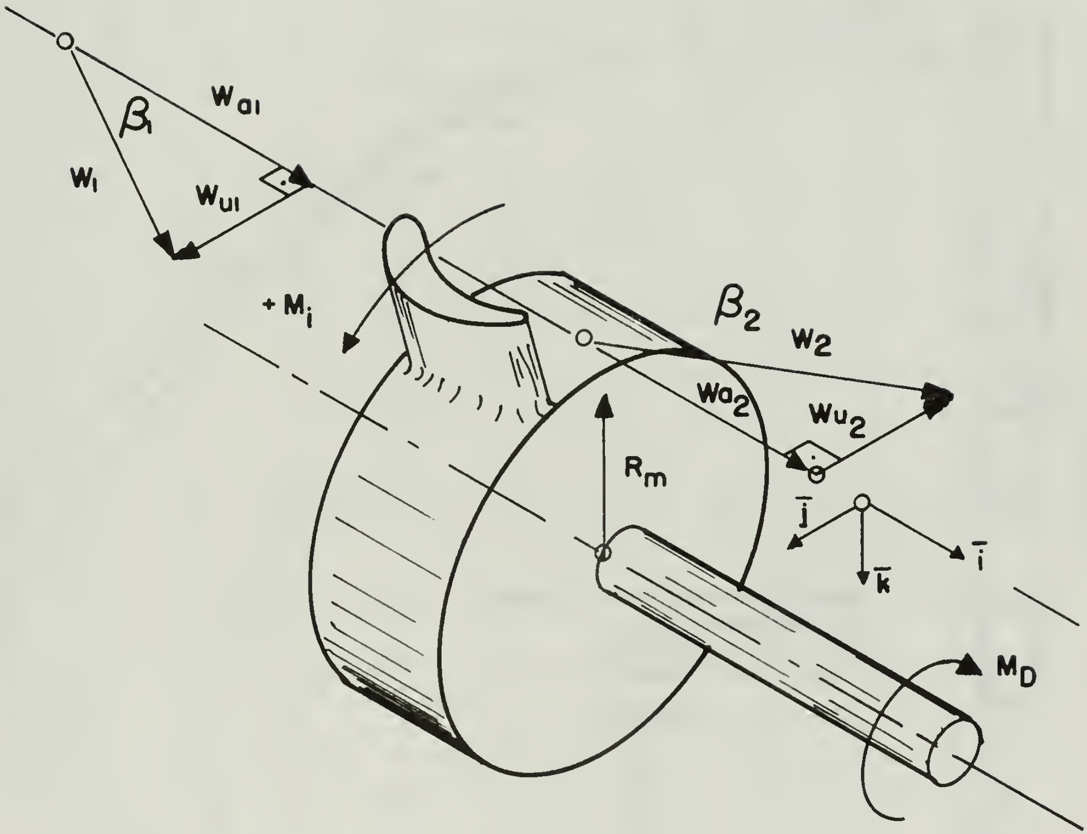
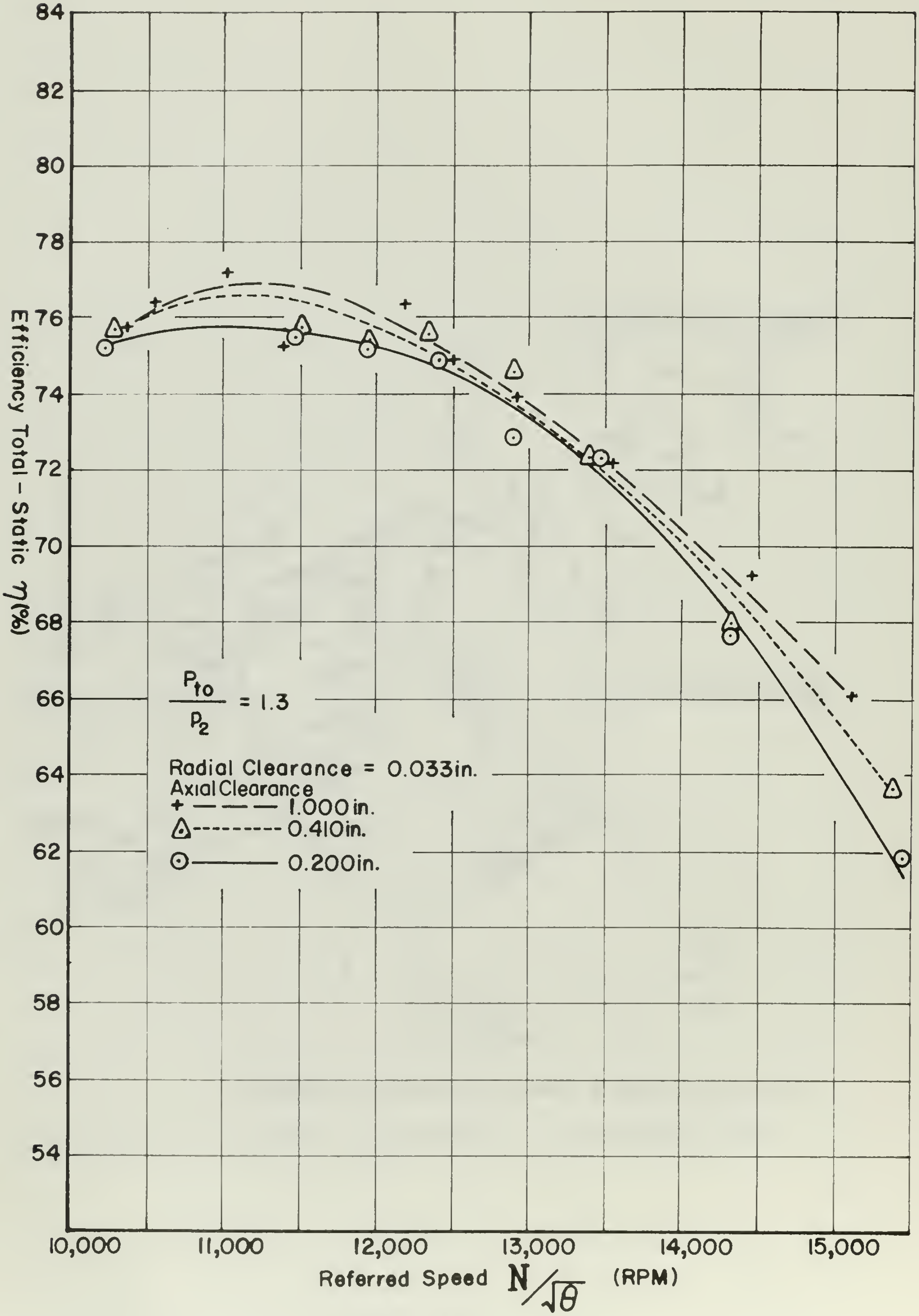


FIGURE 17

VECTOR SYSTEM FOR THE ROTOR ASSEMBLY



84
82
80
78
76
74
72
70
68
66
64
62
60
58
56
54
Efficiency Total - Static η(%)
10,000
11,000
12,000
13,000
14,000
15,000
Referred Speed N/√θ (RPM)
$\frac{P_{to}}{p_2}$ = 1.3
Radial Clearance = 0.033in.
Axial Clearance
1.000 in.
0.410 in.
0.200 in.

FIGURE 18

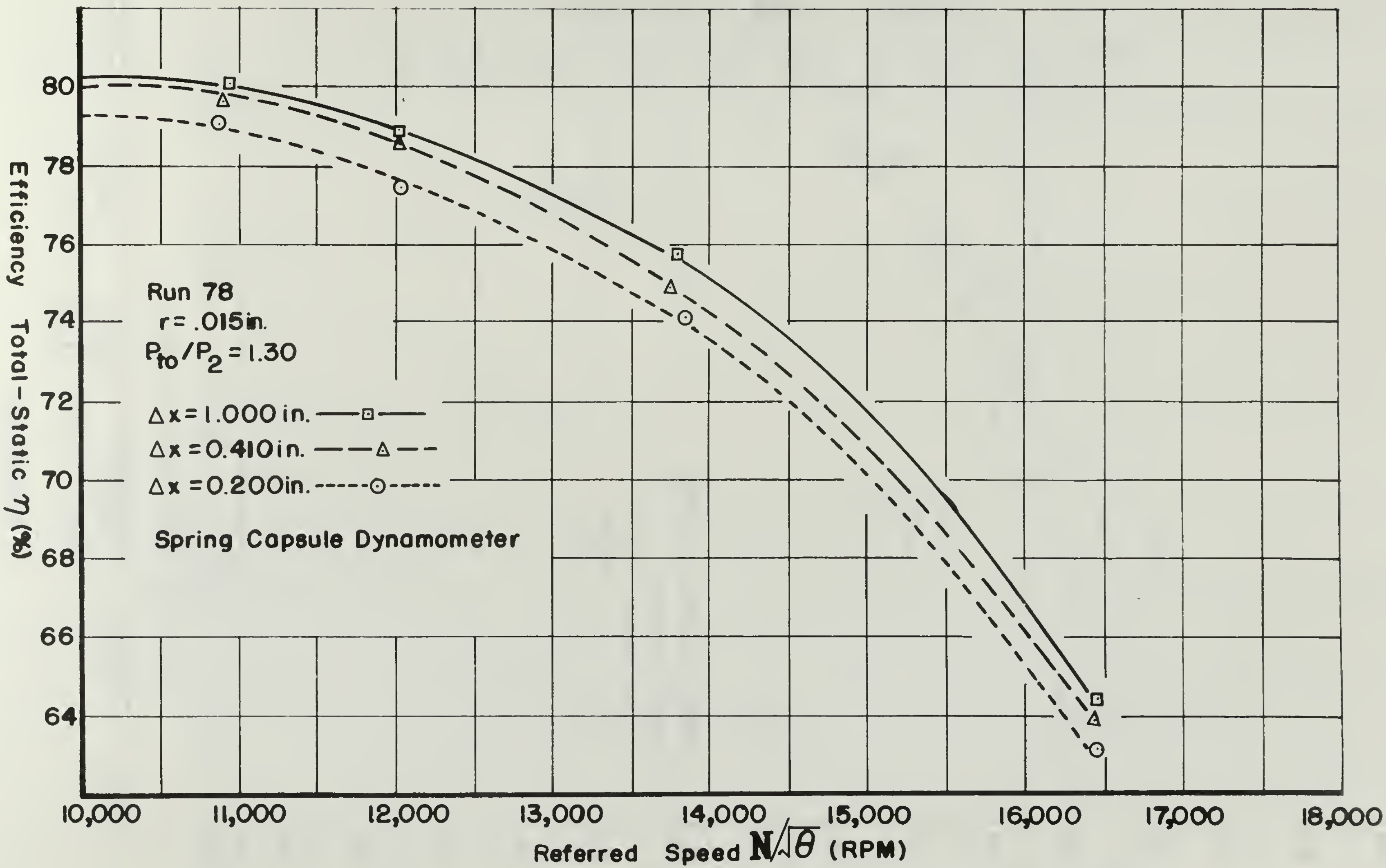
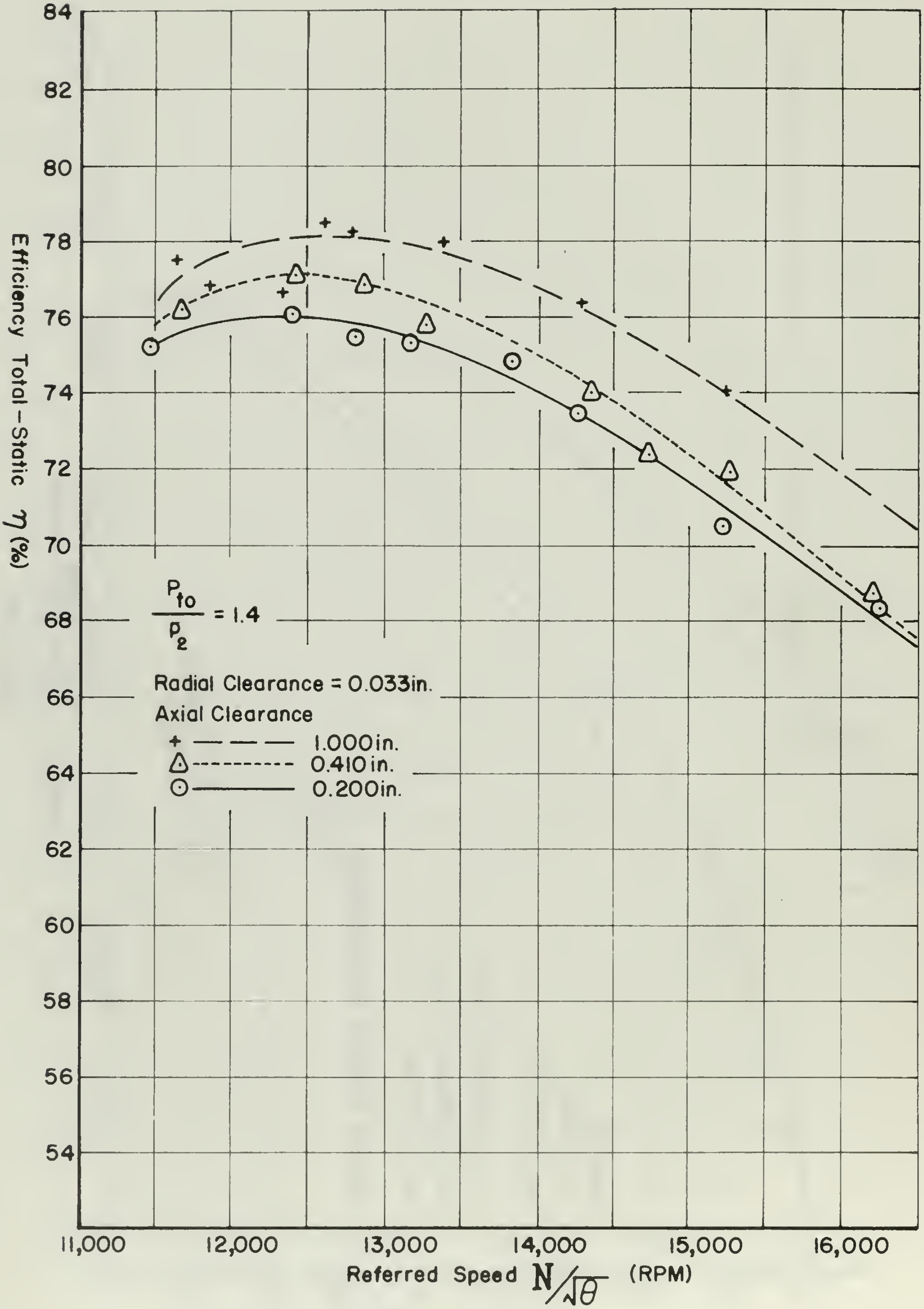

Efficiency Total-Static η (%)
80
78
76
74
72
70
68
66
64
Run 78
r = .015 in.
$P_{to}/P_2 = 1.30$
Δx = 1.000 in.
Δx = 0.410 in.
Δx = 0.200 in.
Spring Capsule Dynamometer
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
Referred Speed $N/\sqrt{\theta}$ (RPM)

FIGURE 19



84
82
80
78
76
74
72
70
68
66
64
62
60
58
56
54
Efficiency Total-Static η (%)
$\frac{P_{to}}{p_2} = 1.4$
Radial Clearance = 0.033in.
Axial Clearance
1.000in.
0.410in.
0.200in.
11,000
12,000
13,000
14,000
15,000
16,000
Referred Speed $N/\sqrt{\theta}$ (RPM)

FIGURE 20

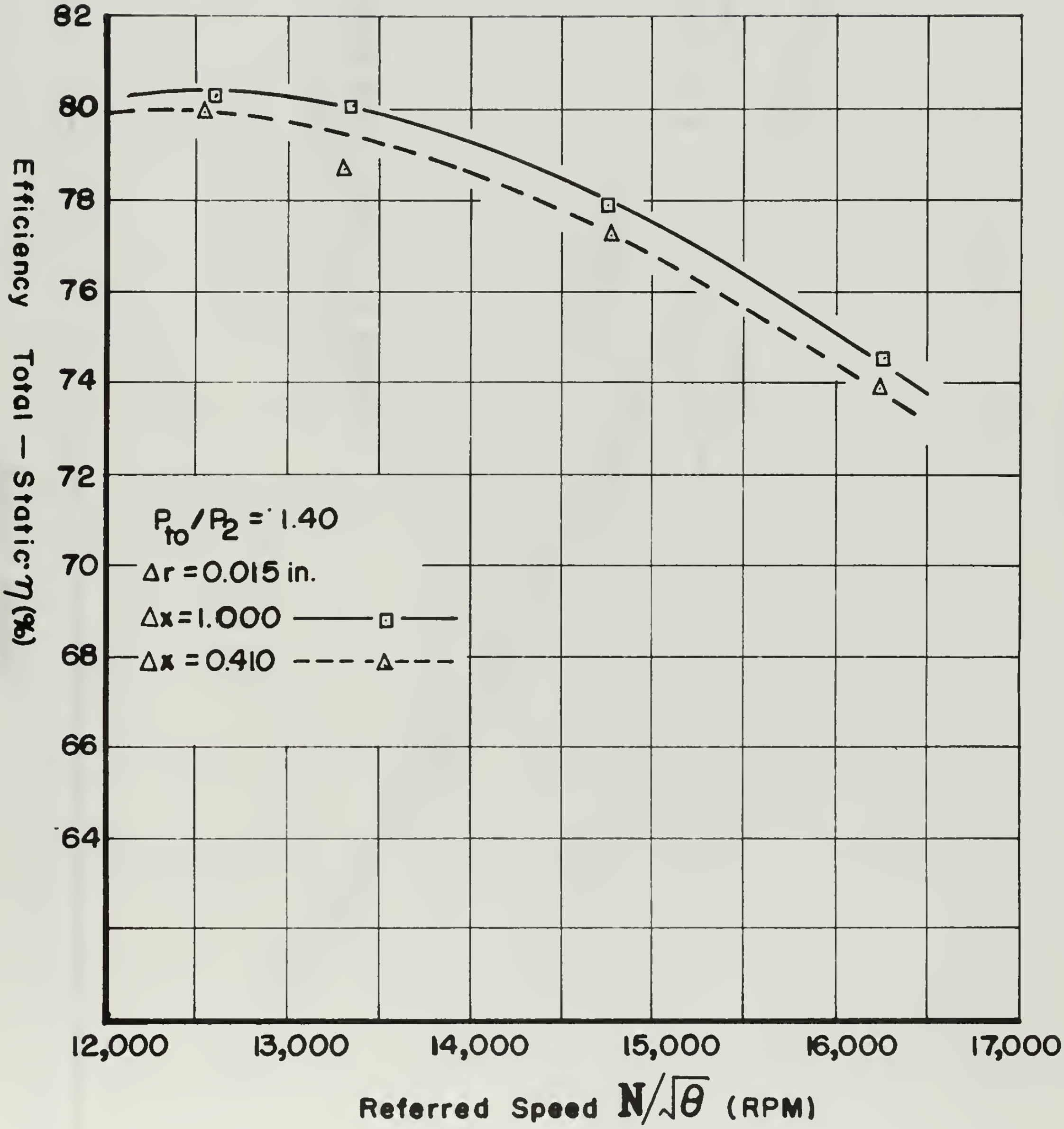

82
80
78
76
74
72
70
68
66
64
Efficiency Total — Static η (%)
P_{to}/P_2 = 1.40
Δr = 0.015 in.
Δx = 1.000
Δx = 0.410
12,000
13,000
14,000
15,000
16,000
17,000
Referred Speed $N/\sqrt{\theta}$ (RPM)

FIGURE 21

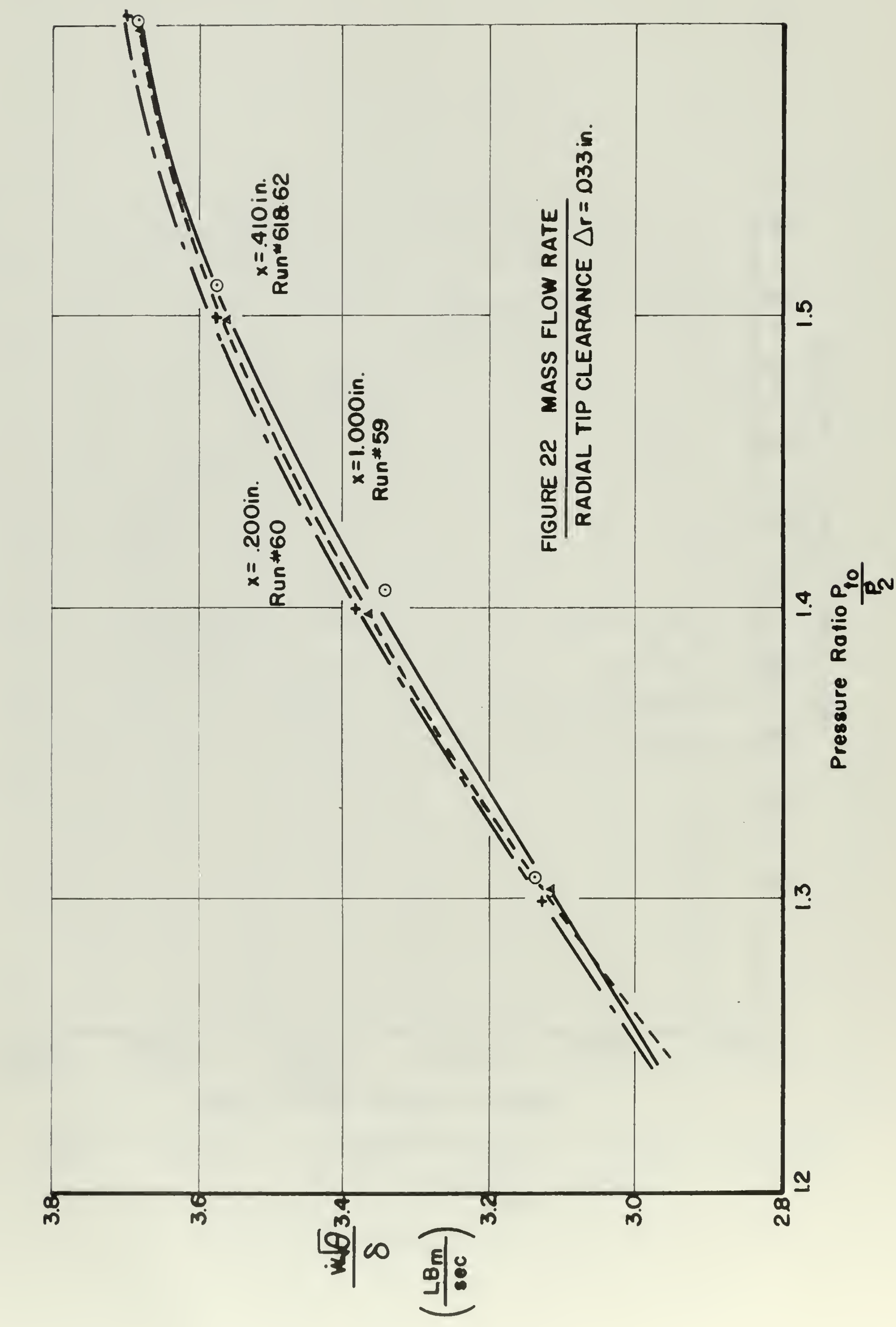


FIGURE 22 MASS FLOW RATE

RADIAL TIP CLEARANCE Δr = .033 in.

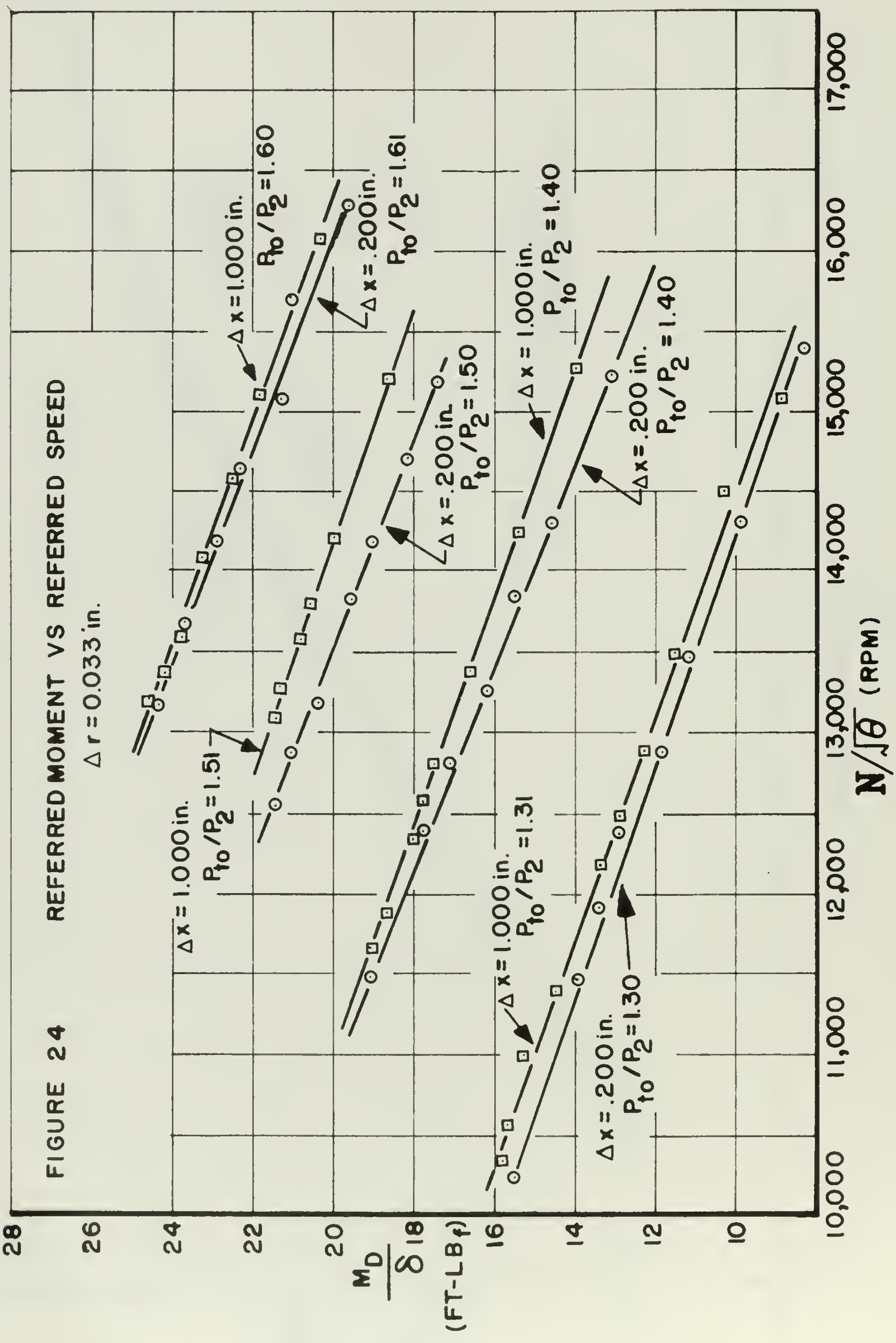
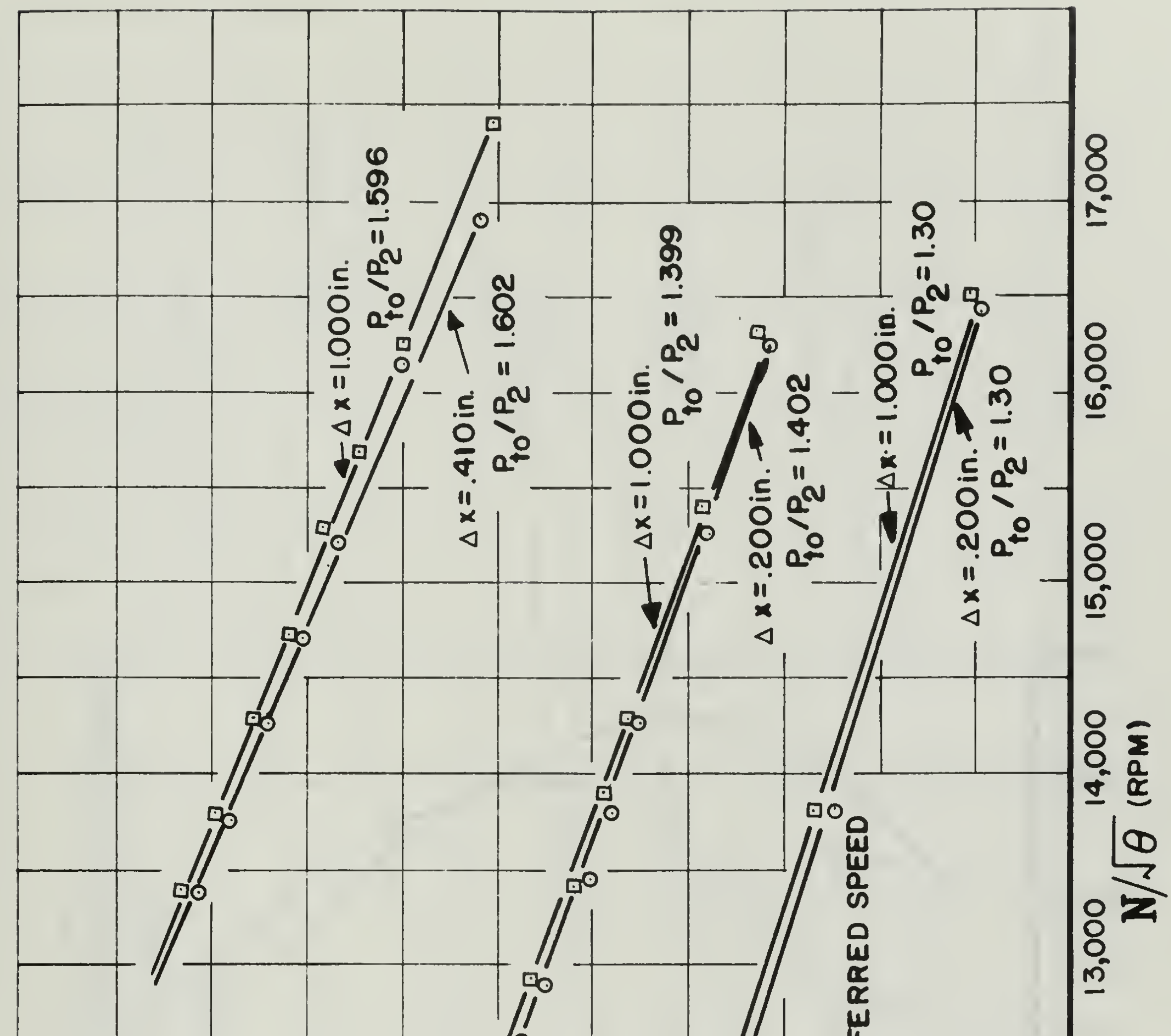


FIGURE 24
REFERRED MOMENT VS REFERRED SPEED
Δ r = 0.033 in.
Δ x = 1.000 in. P_{to}/P_2 = 1.60
Δ x = .200 in. P_{to}/P_2 = 1.61
Δ x = 1.000 in. P_{to}/P_2 = 1.51
Δ x = .200 in. P_{to}/P_2 = 1.50
Δ x = 1.000 in. P_{to}/P_2 = 1.40
Δ x = .200 in. P_{to}/P_2 = 1.40
Δ x = 1.000 in. P_{to}/P_2 = 1.31
Δ x = .200 in. P_{to}/P_2 = 1.30
$\frac{M_D}{\delta}$ (FT-LB$_f$)
28
26
24
22
20
18
16
14
12
10
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
$N/\sqrt{\theta}$ (RPM)



REFERRED MOMENT VS REFERRED SPEED

$\Delta r = 0.015$ in.

FIGURE 25

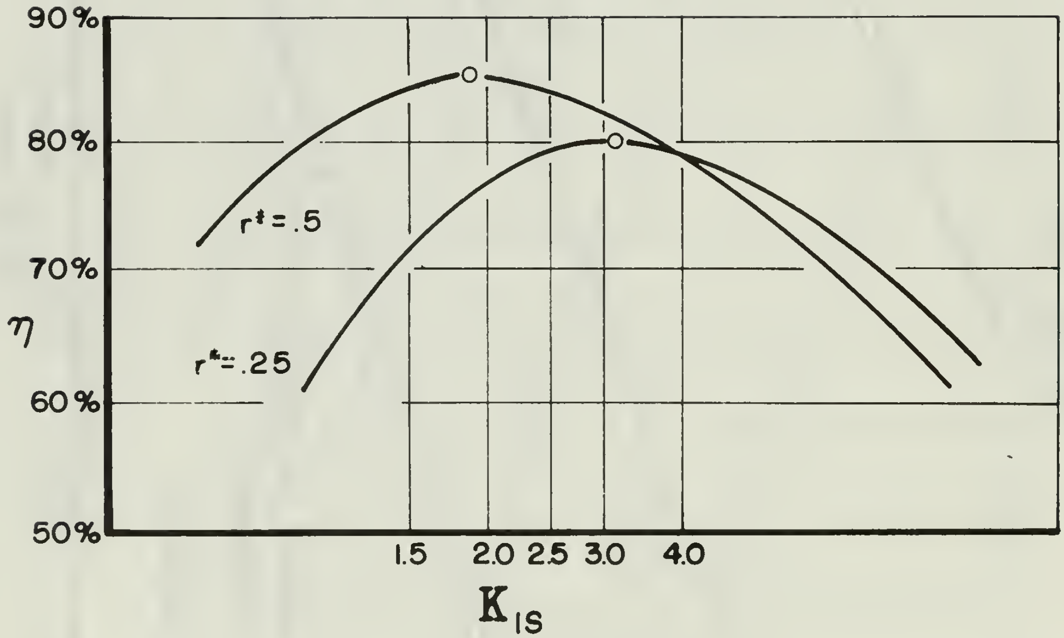


FIGURE 26

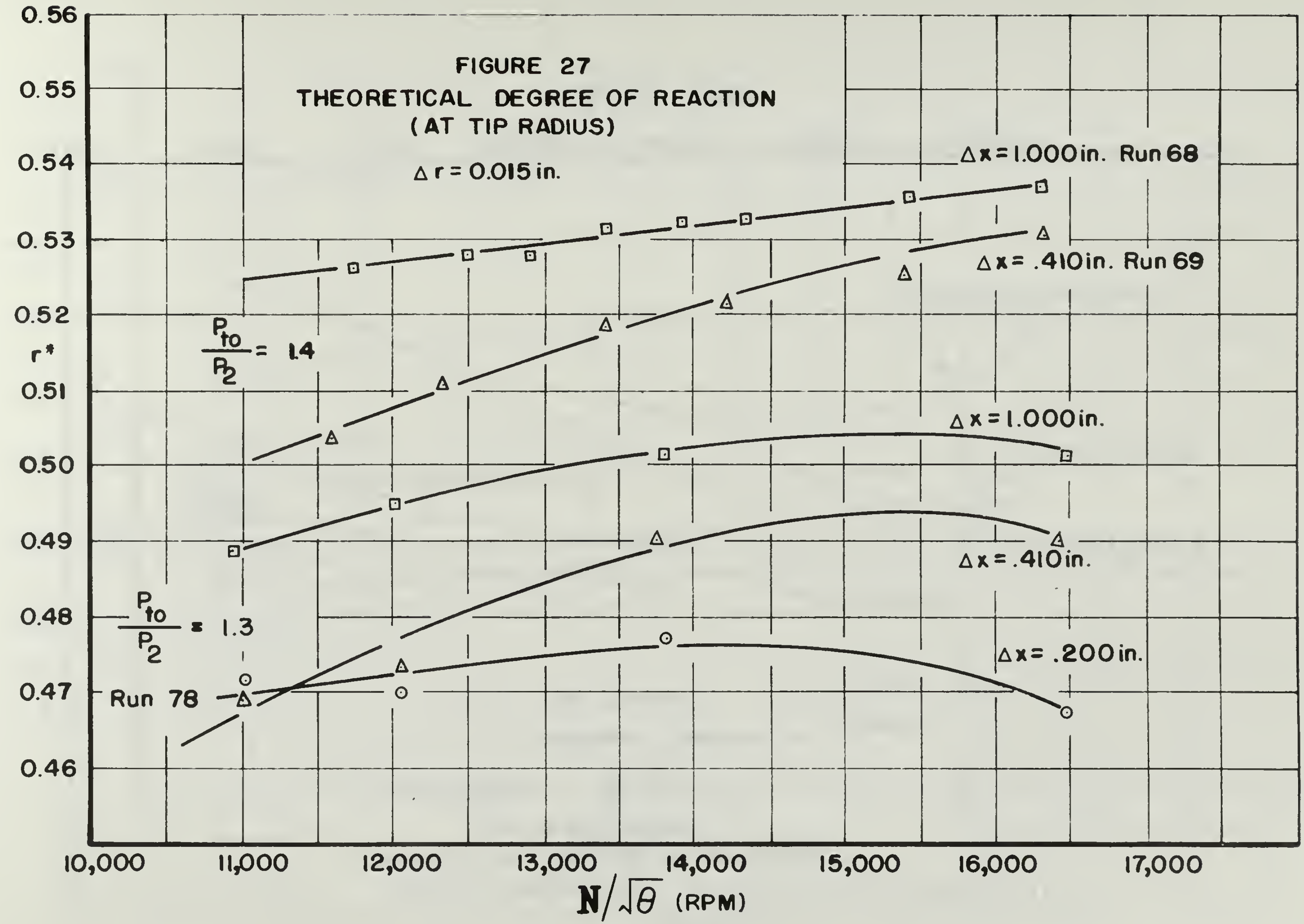


FIGURE 27
THEORETICAL DEGREE OF REACTION
(AT TIP RADIUS)
Δ r = 0.015 in.
Δ x = 1.000 in. Run 68
Δ x = .410 in. Run 69
Δ x = 1.000 in.
Δ x = .410 in.
Δ x = .200 in.
$\frac{P_{to}}{P_2} = 1.4$
$\frac{P_{to}}{P_2} = 1.3$
Run 78
0.56
0.55
0.54
0.53
0.52
r*
0.51
0.50
0.49
0.48
0.47
0.46
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
$N/\sqrt{\theta}$ (RPM)

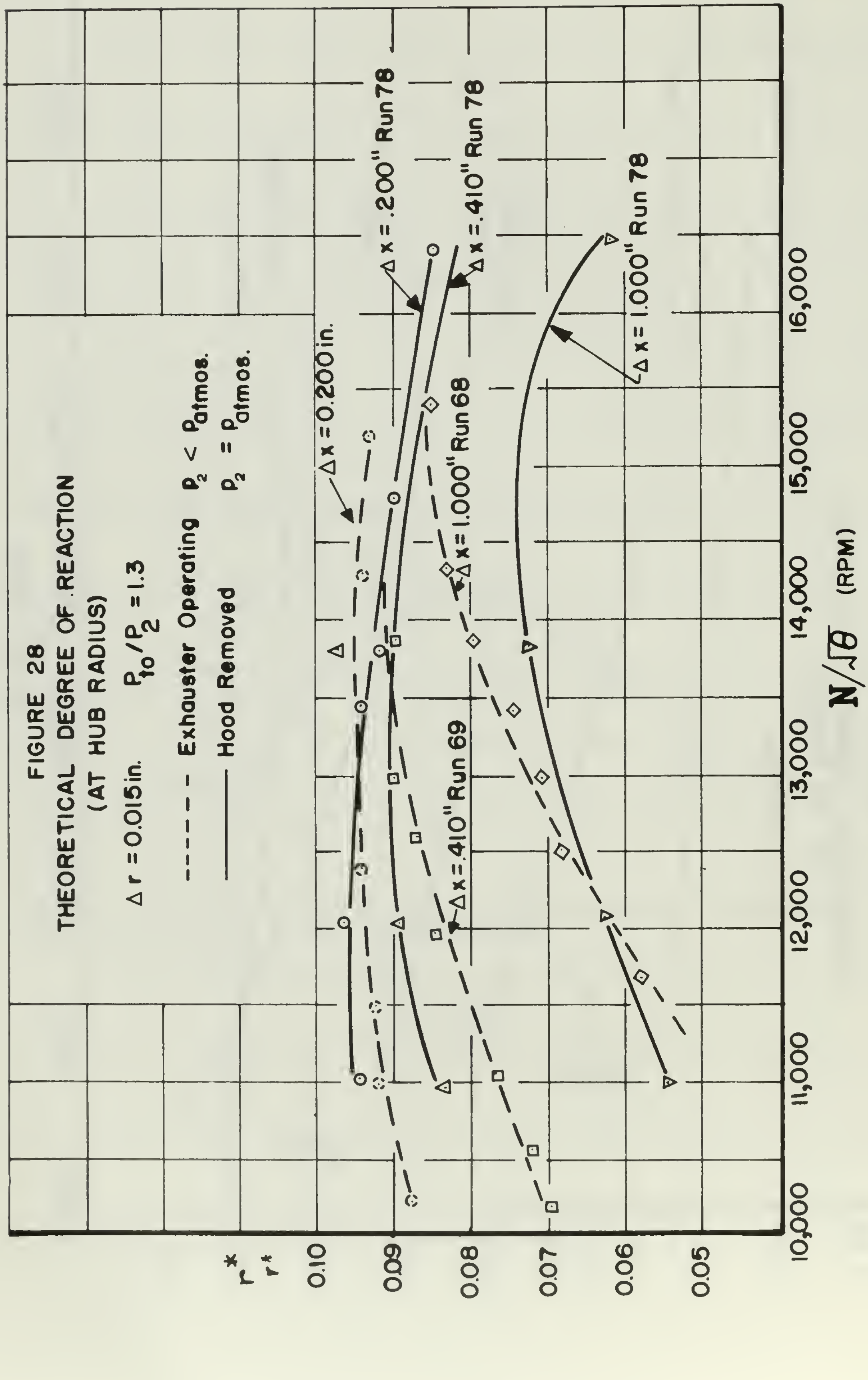
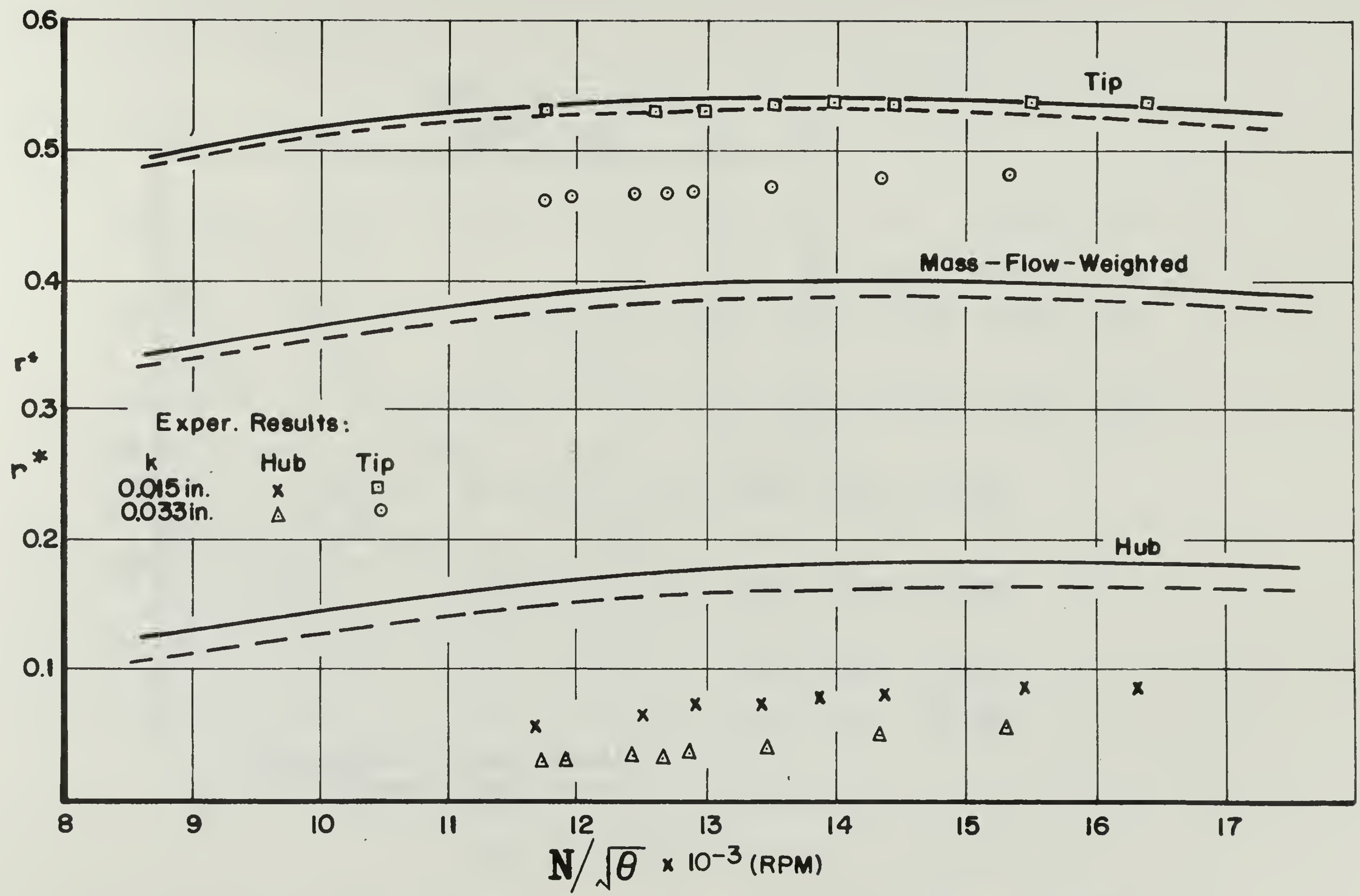


FIGURE 28
THEORETICAL DEGREE OF REACTION
(AT HUB RADIUS)



THEORETICAL DEGREE OF REACTION VS REFERRED RPM

FIGURE 29

FIGURE 30
EFFICIENCY TOTAL-STATIC

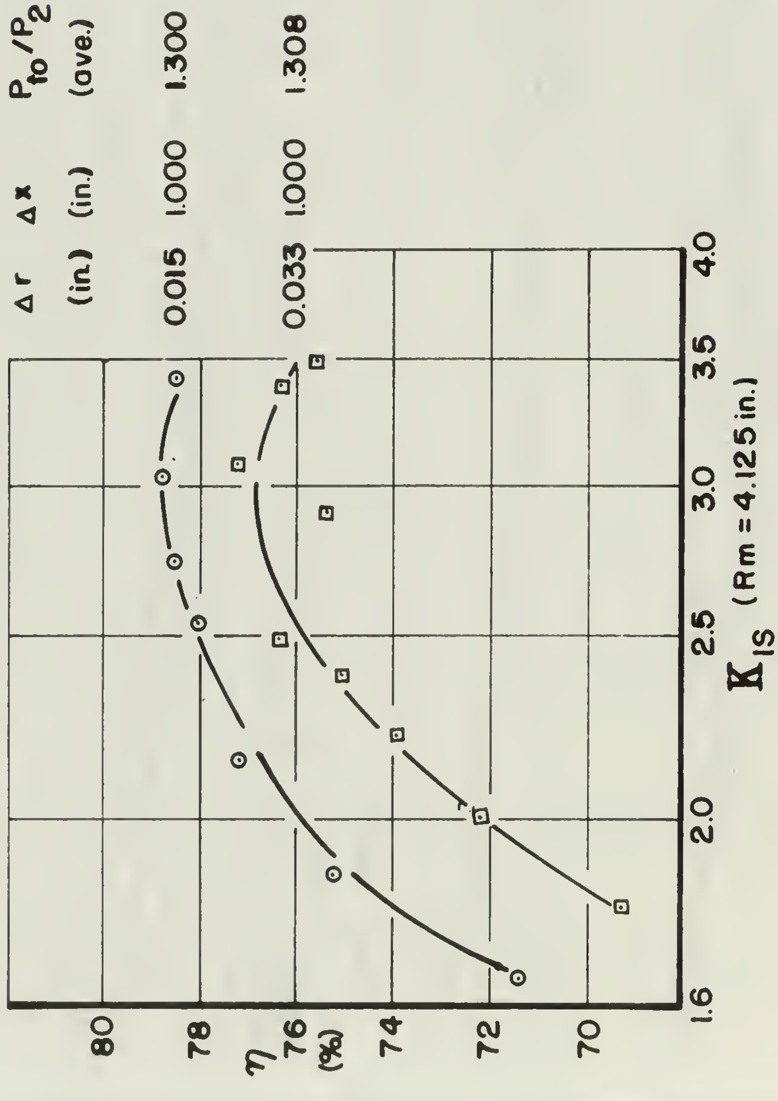


FIGURE 31
EFFICIENCY TOTAL-STATIC

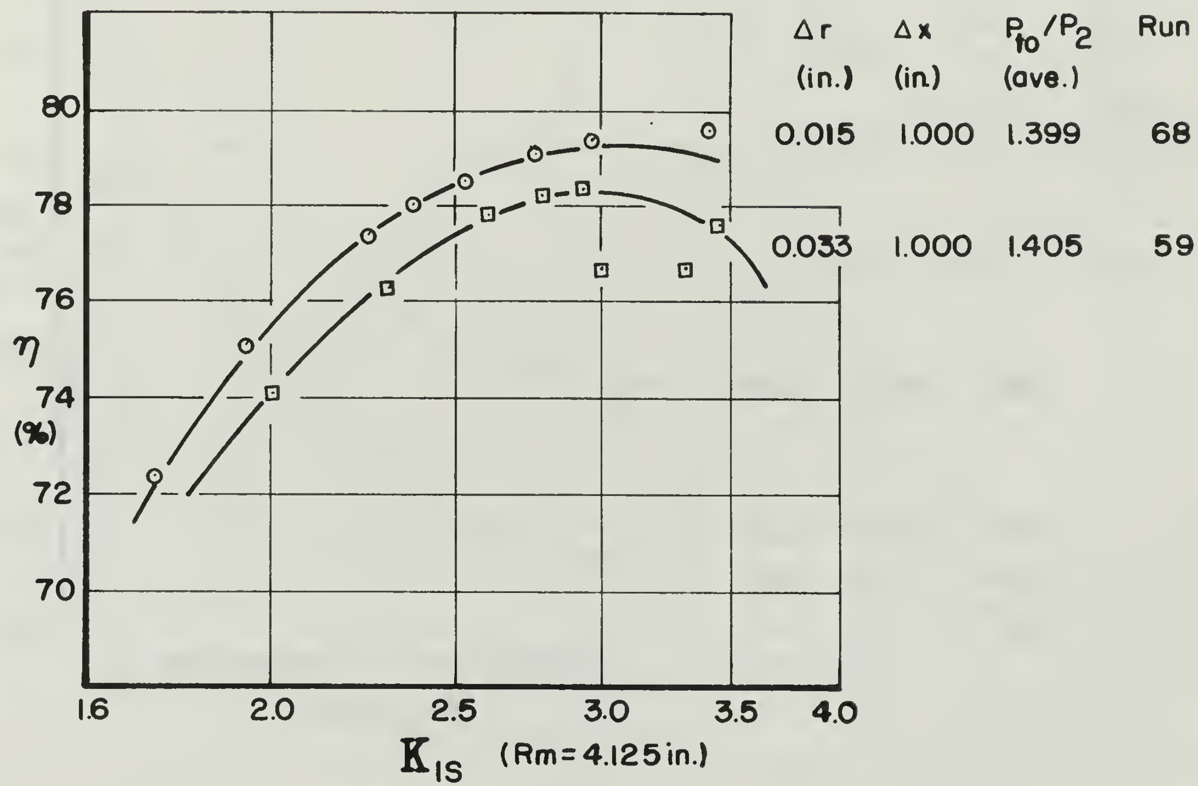


FIGURE 32

EFFICIENCY TOTAL-STATIC

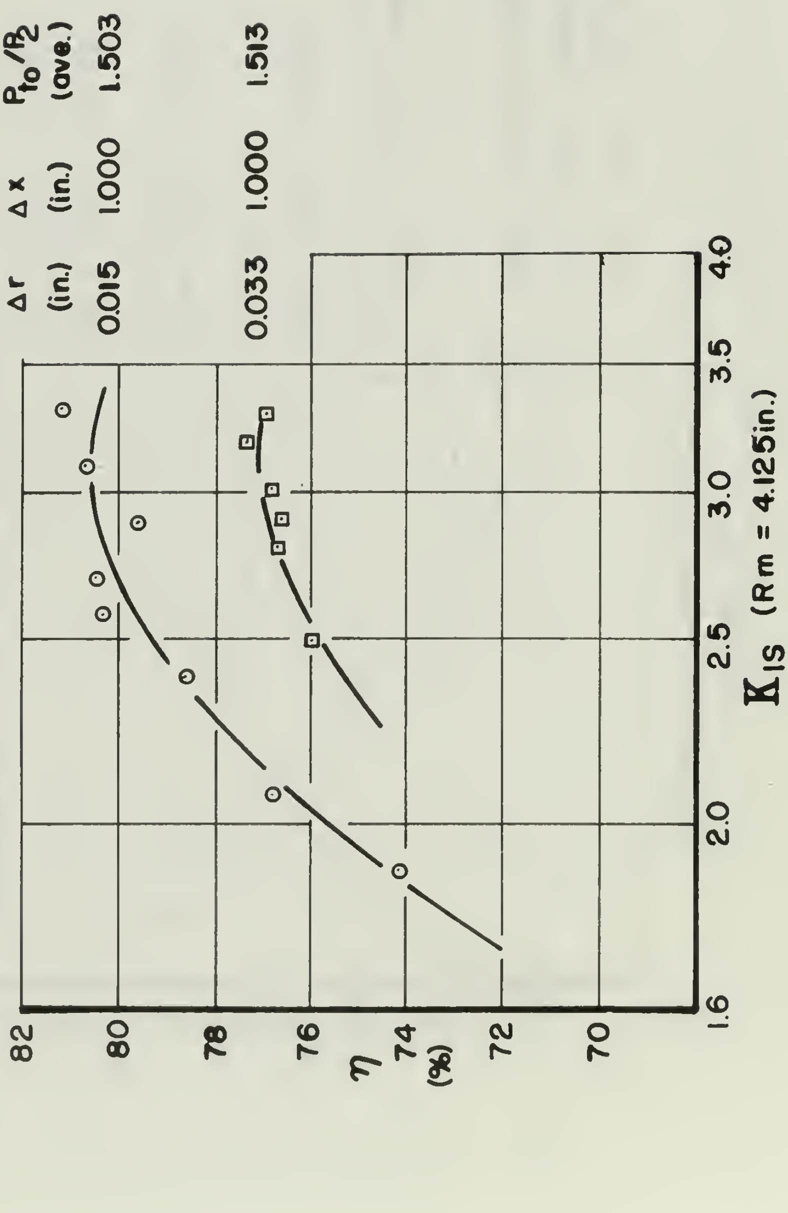
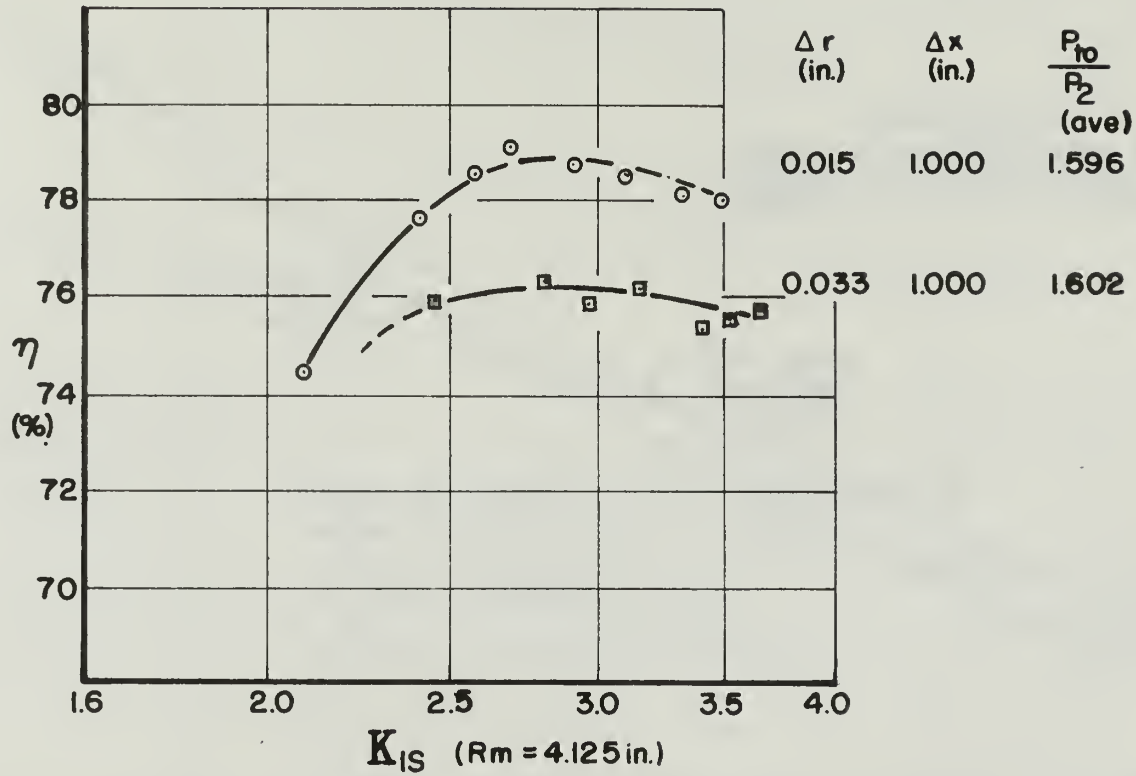


FIGURE 33

EFFICIENCY TOTAL—STATIC



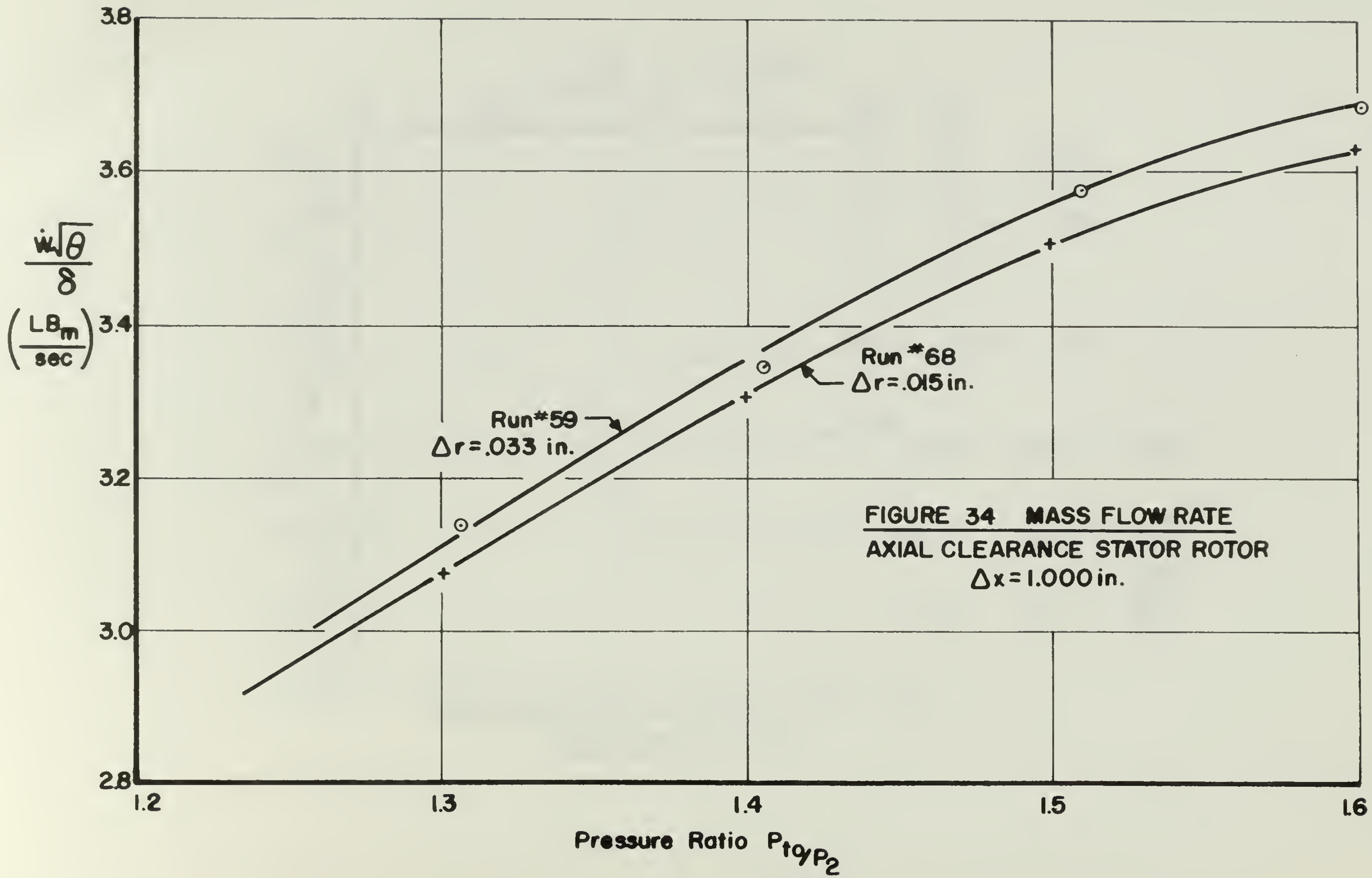


FIGURE 34 MASS FLOW RATE
AXIAL CLEARANCE STATOR ROTOR
Δx = 1.000 in.

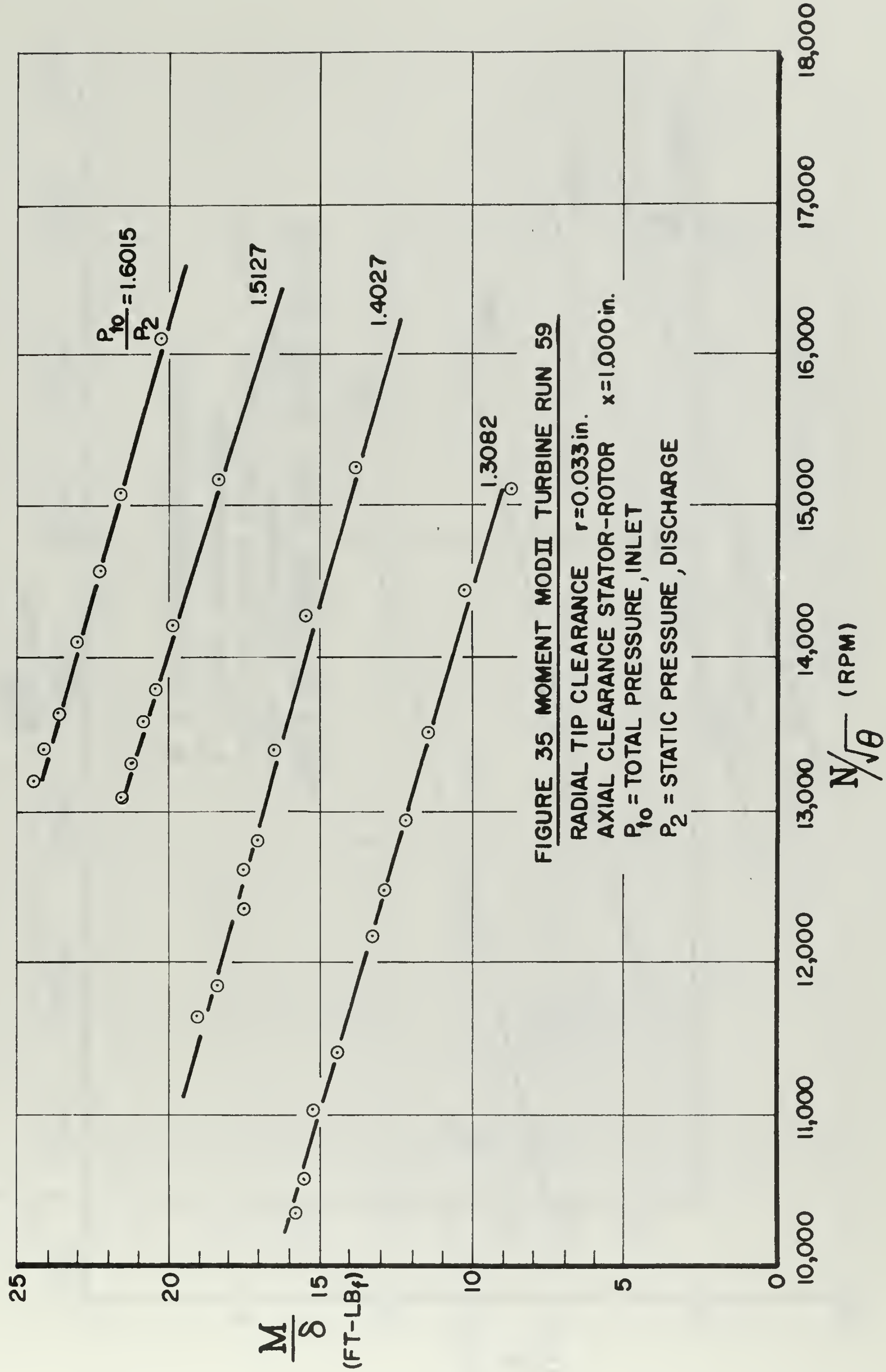


FIGURE 35 MOMENT MODII TURBINE RUN 59
RADIAL TIP CLEARANCE r=0.033 in.
AXIAL CLEARANCE STATOR-ROTOR x=1.000 in.
P_{t0} = TOTAL PRESSURE, INLET
P_2 = STATIC PRESSURE, DISCHARGE
$\frac{P_{t0}}{P_2}$ = 1.6015
1.5127
1.4027
1.3082
$\frac{M}{\delta}$ (FT-LB$_f$)
25
20
15
10
5
0
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
$N/\sqrt{\theta}$ (RPM)

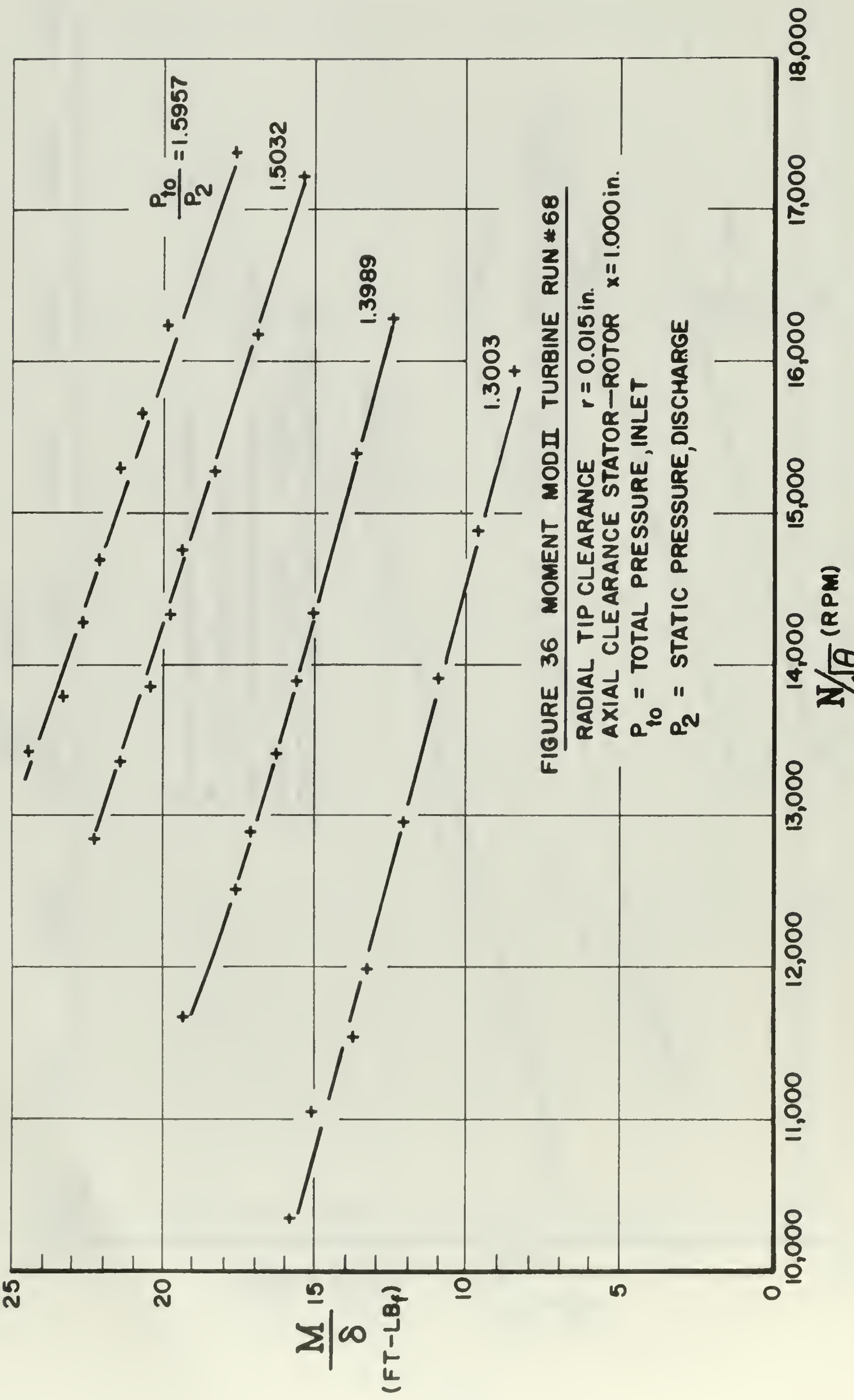
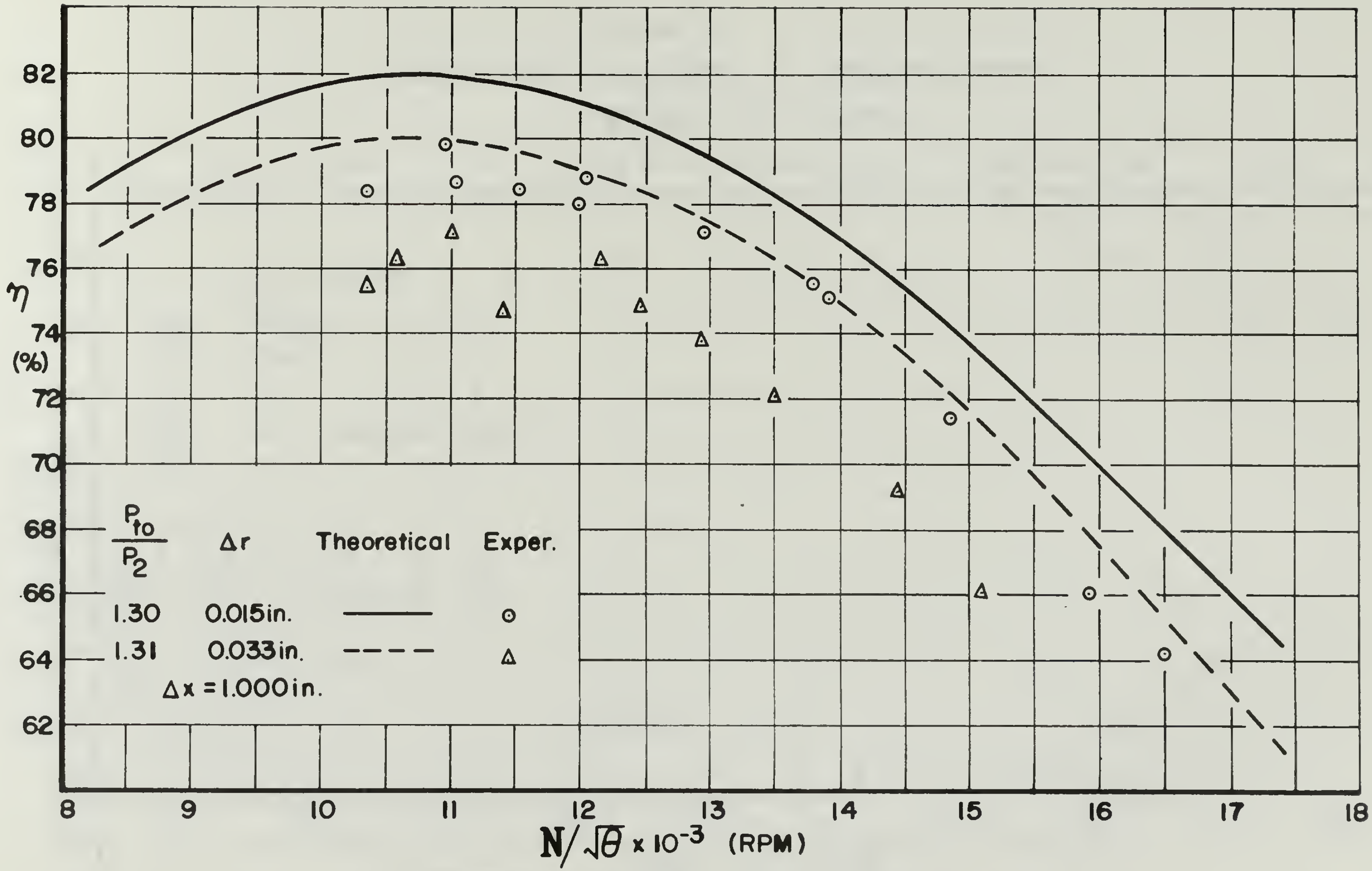
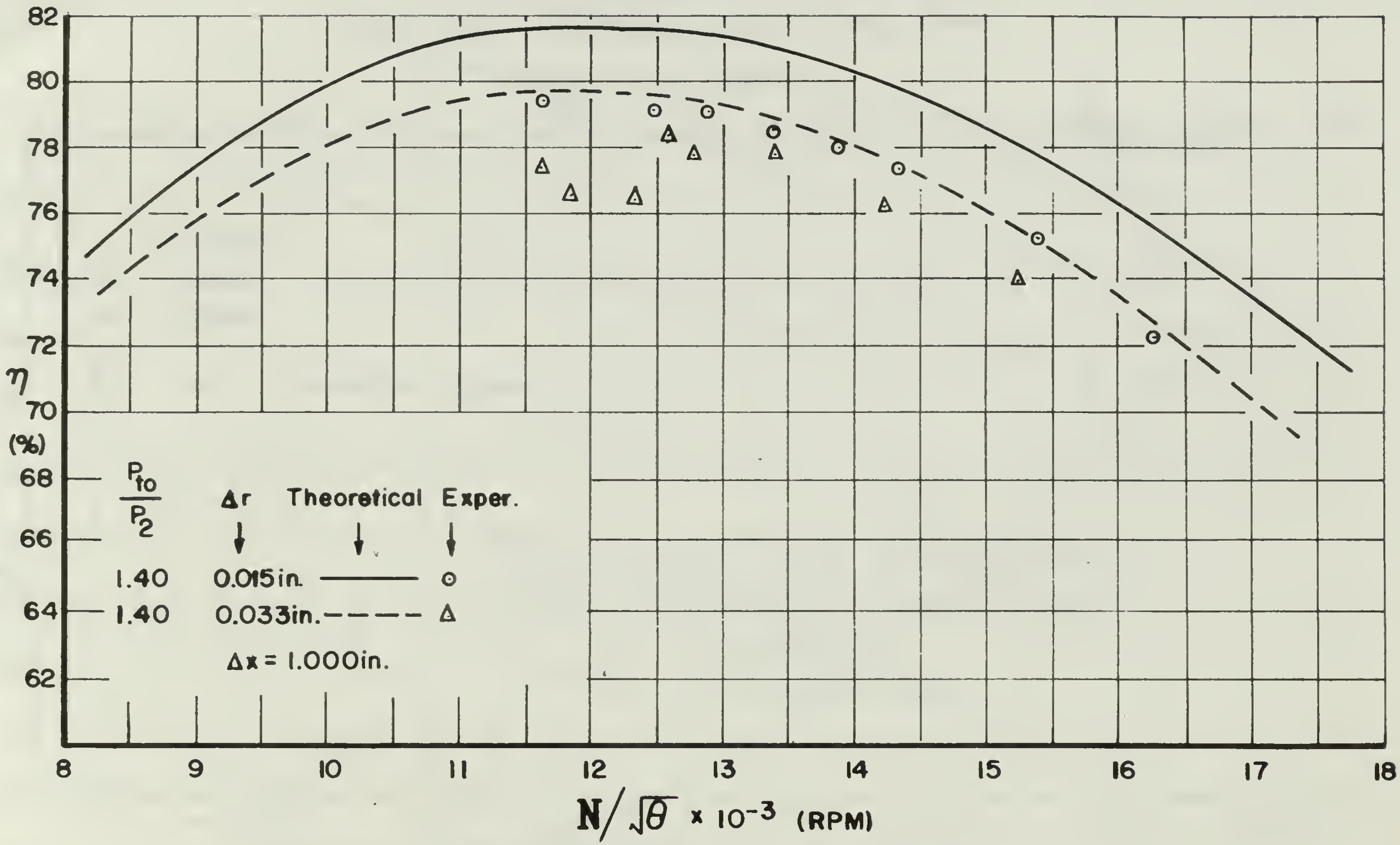


FIGURE 36 MOMENT MOD II TURBINE RUN #68



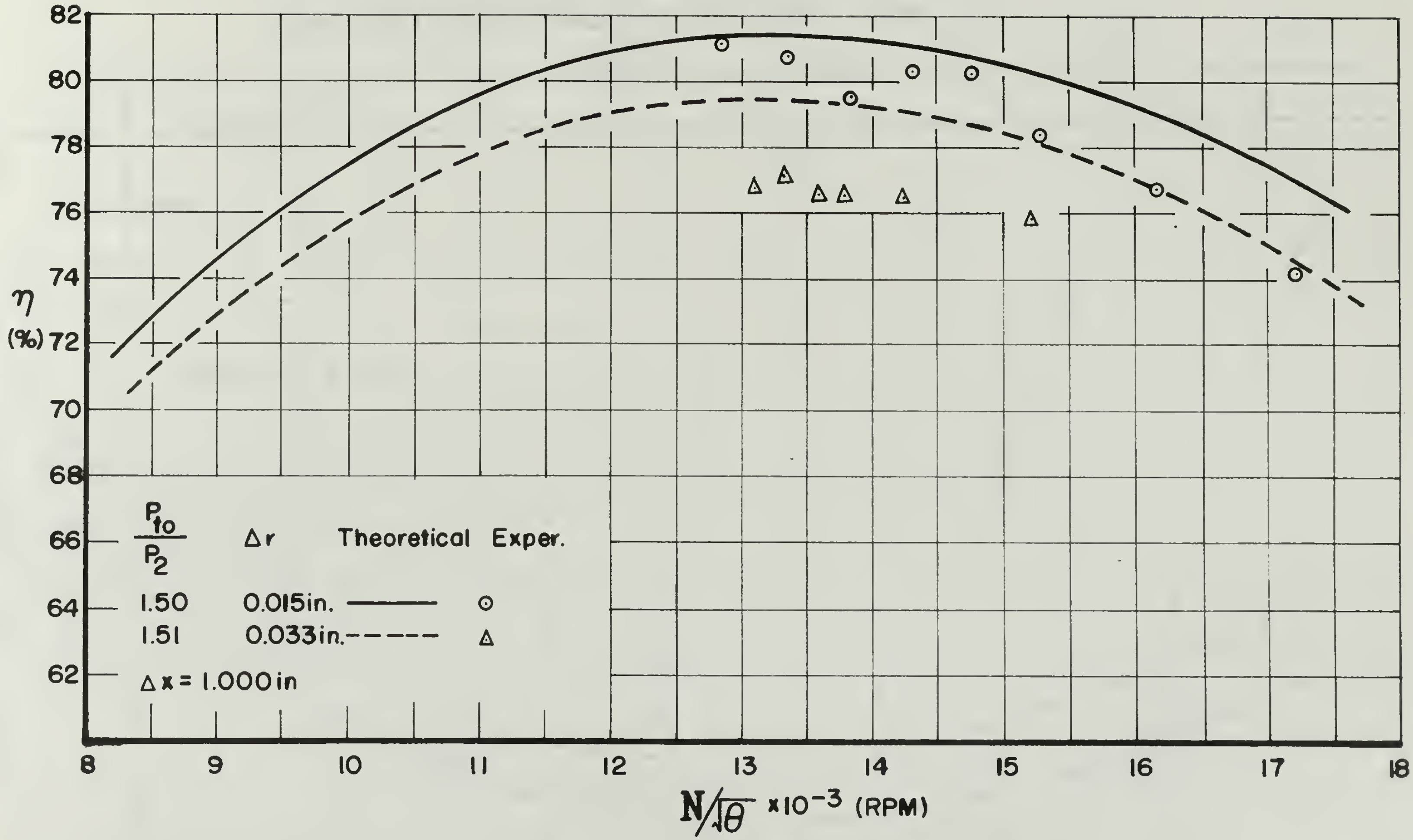
TOTAL-STATIC EFFICIENCY VS REFERRED RPM

FIGURE 37



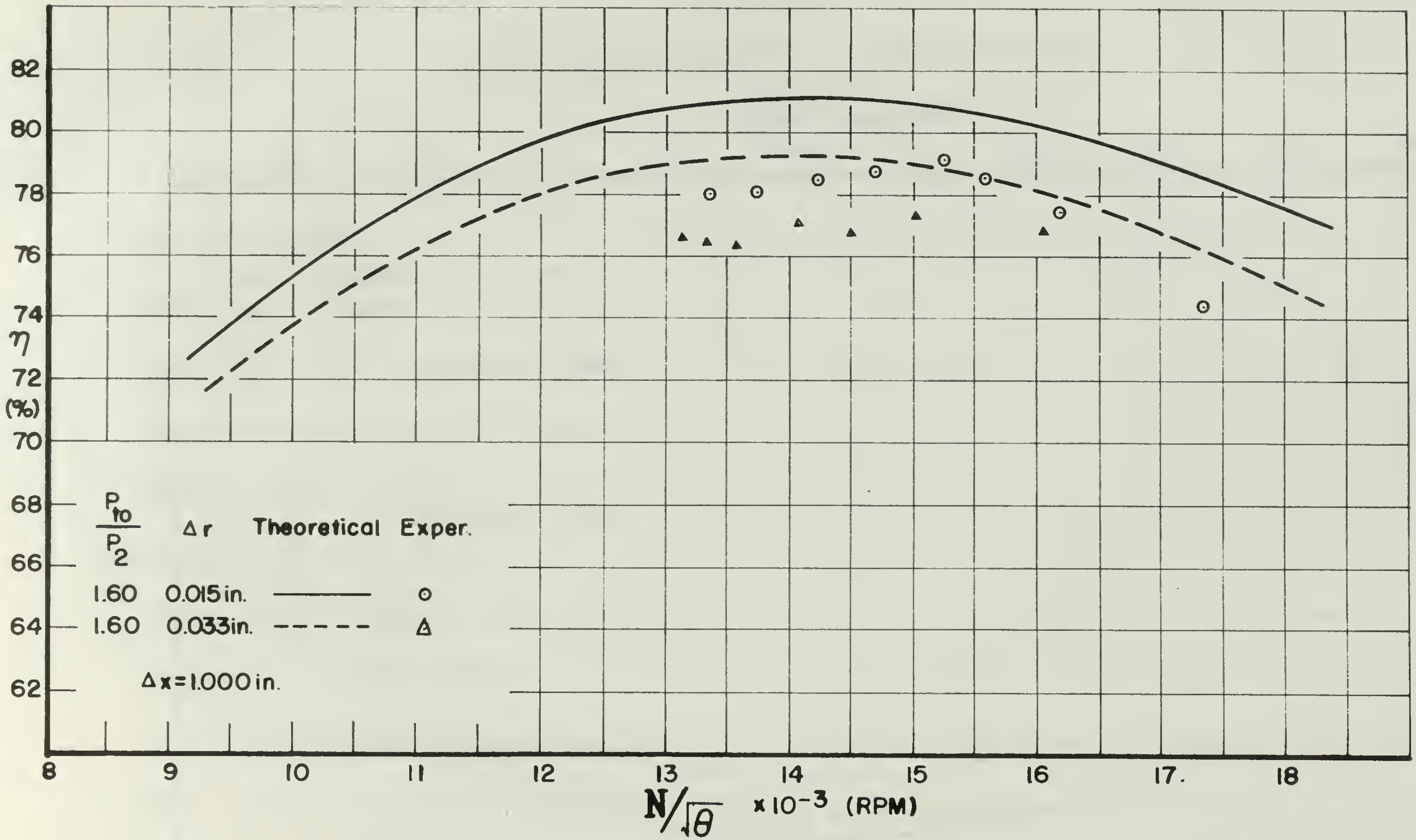
TOTAL-STATIC EFFICIENCY VS REFERRED RPM

FIGURE 38



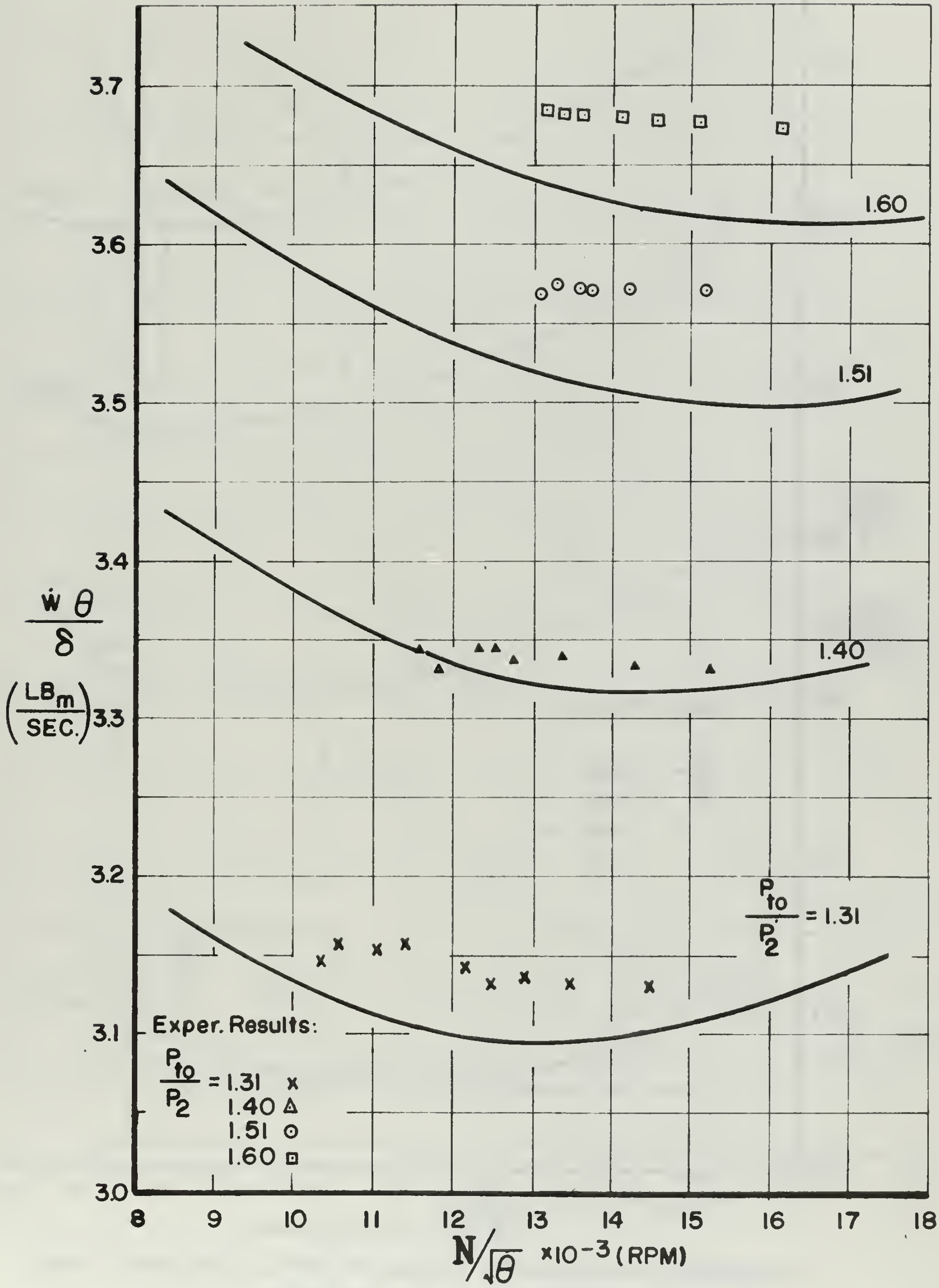
TOTAL-STATIC EFFICIENCY VS REFERRED RPM

FIGURE 39



TOTAL-STATIC EFFICIENCY VS REFERRED RPM

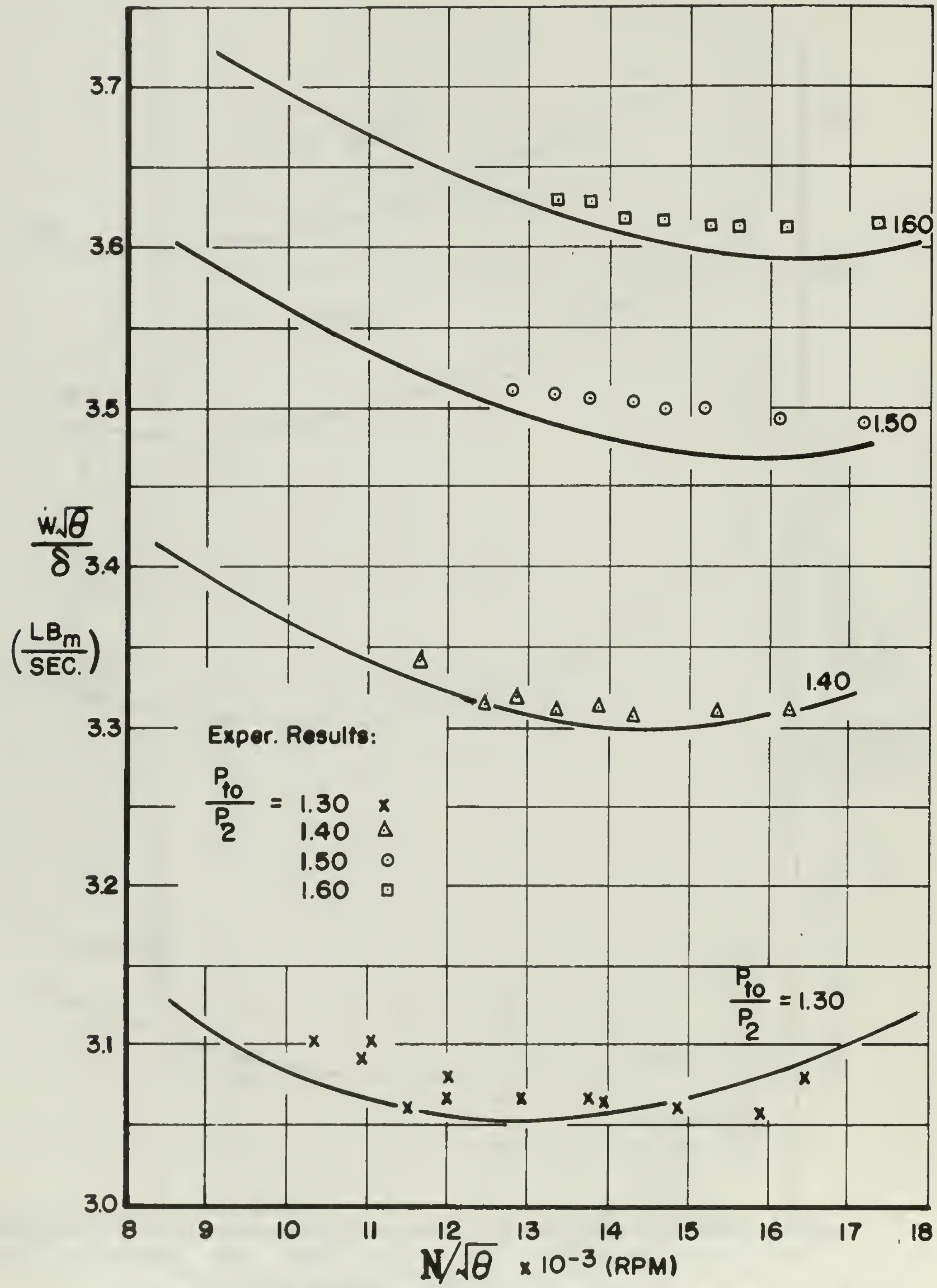
FIGURE 40



VARIATION OF REFERRED FLOWRATE WITH REFERRED RPM

$\Delta r = .033$ in. $\Delta x = 1.000$ in.

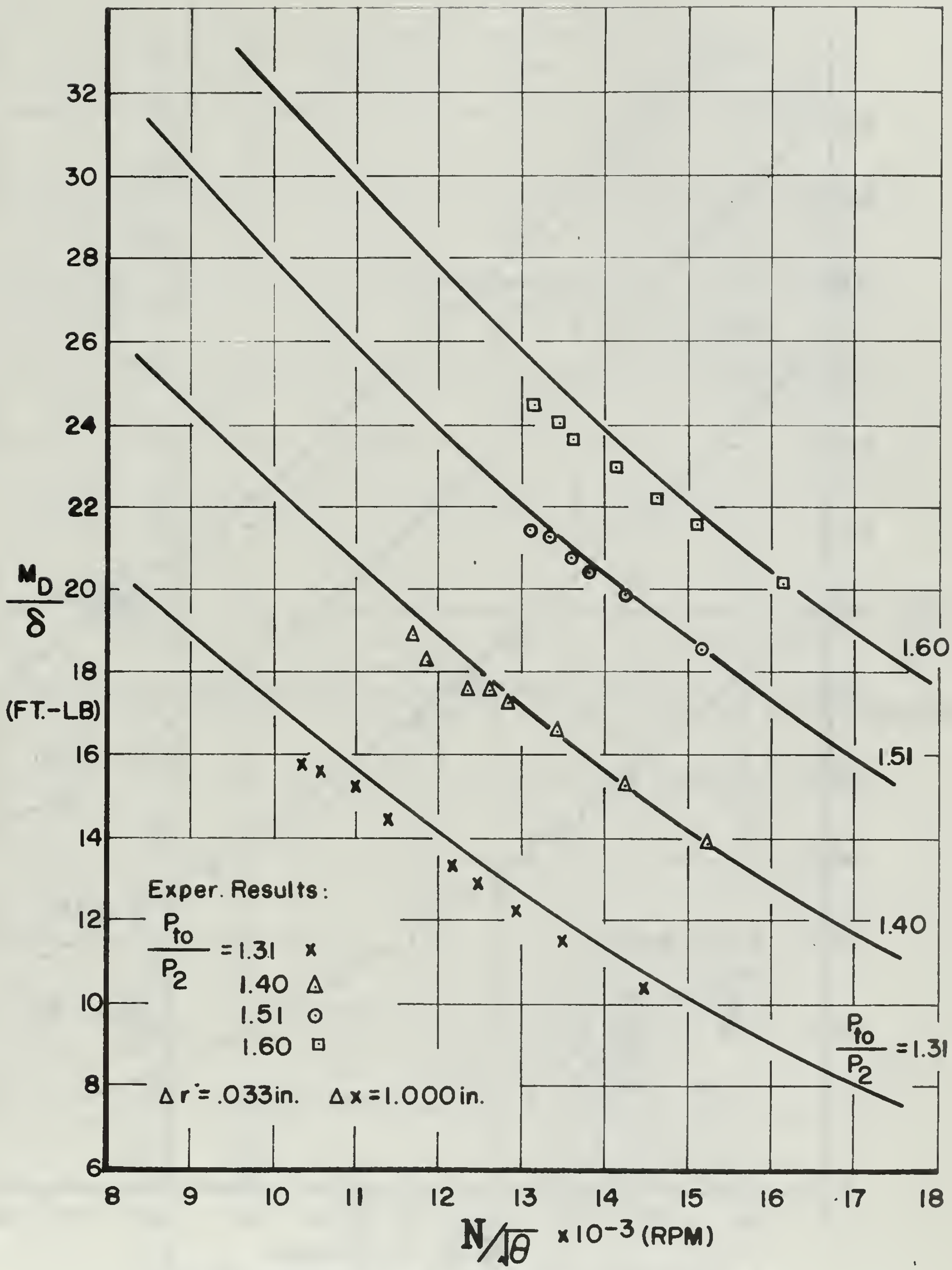
FIGURE 41



VARIATION OF REFERRED FLOWRATE WITH REFERRED RPM

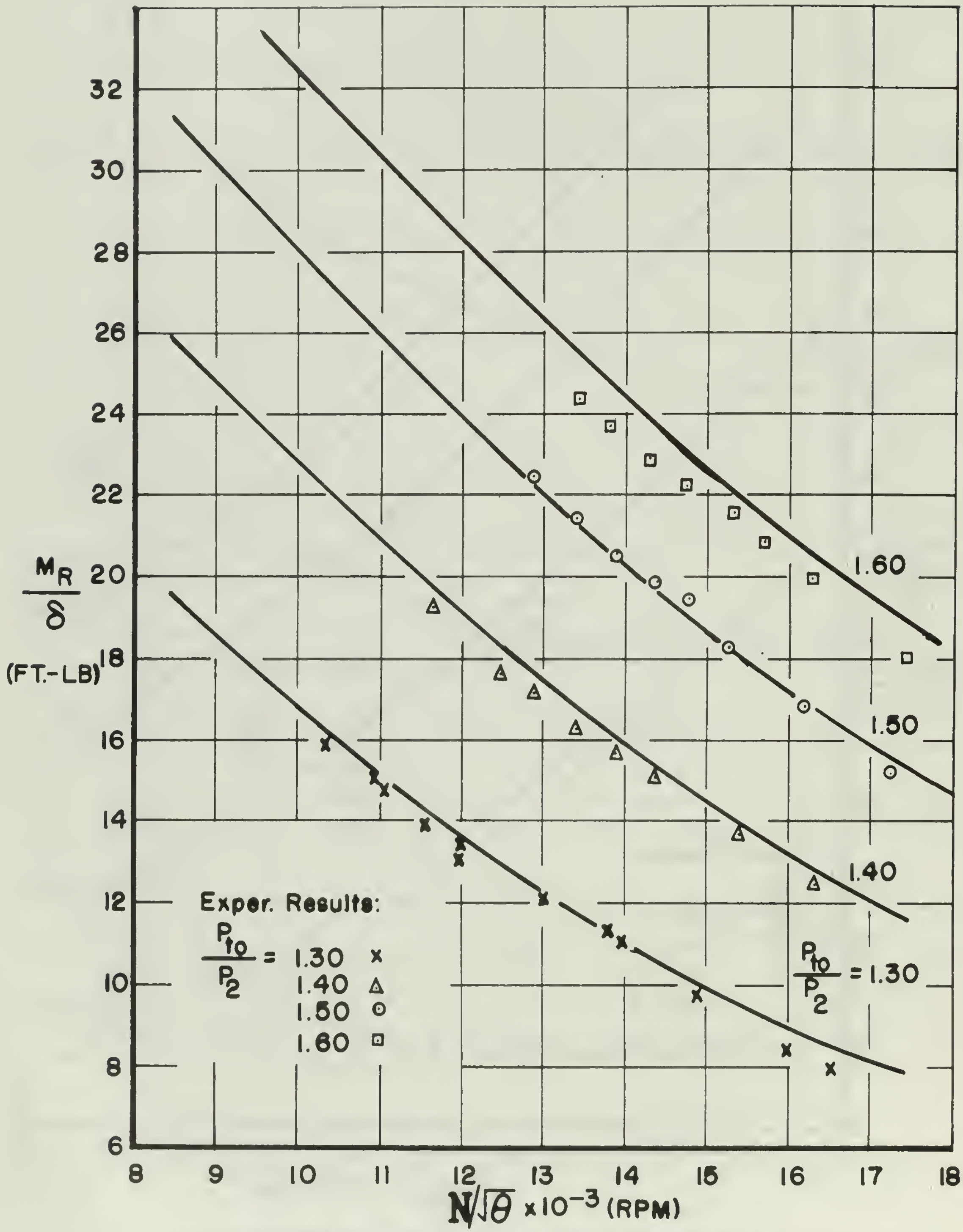
$\Delta r = 0.015$ in. $\Delta x = 1.000$ in.

FIGURE 42



REFERRED MOMENT VS REFERRED RPM

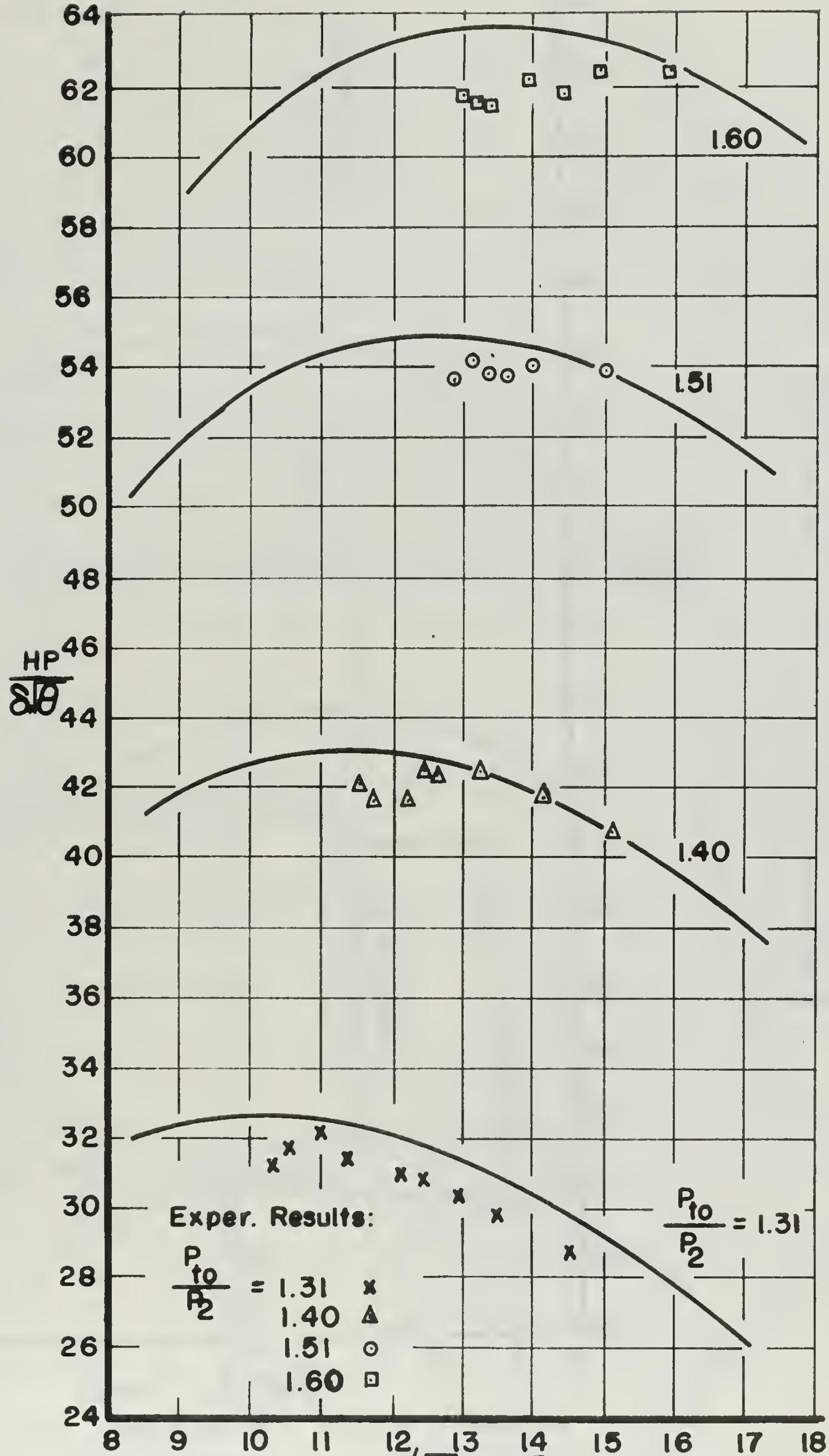
FIGURE 43



REFERRED MOMENT VS REFERRED RPM

$\Delta x = 1.000$ in. $\Delta r = 0.015$ in.

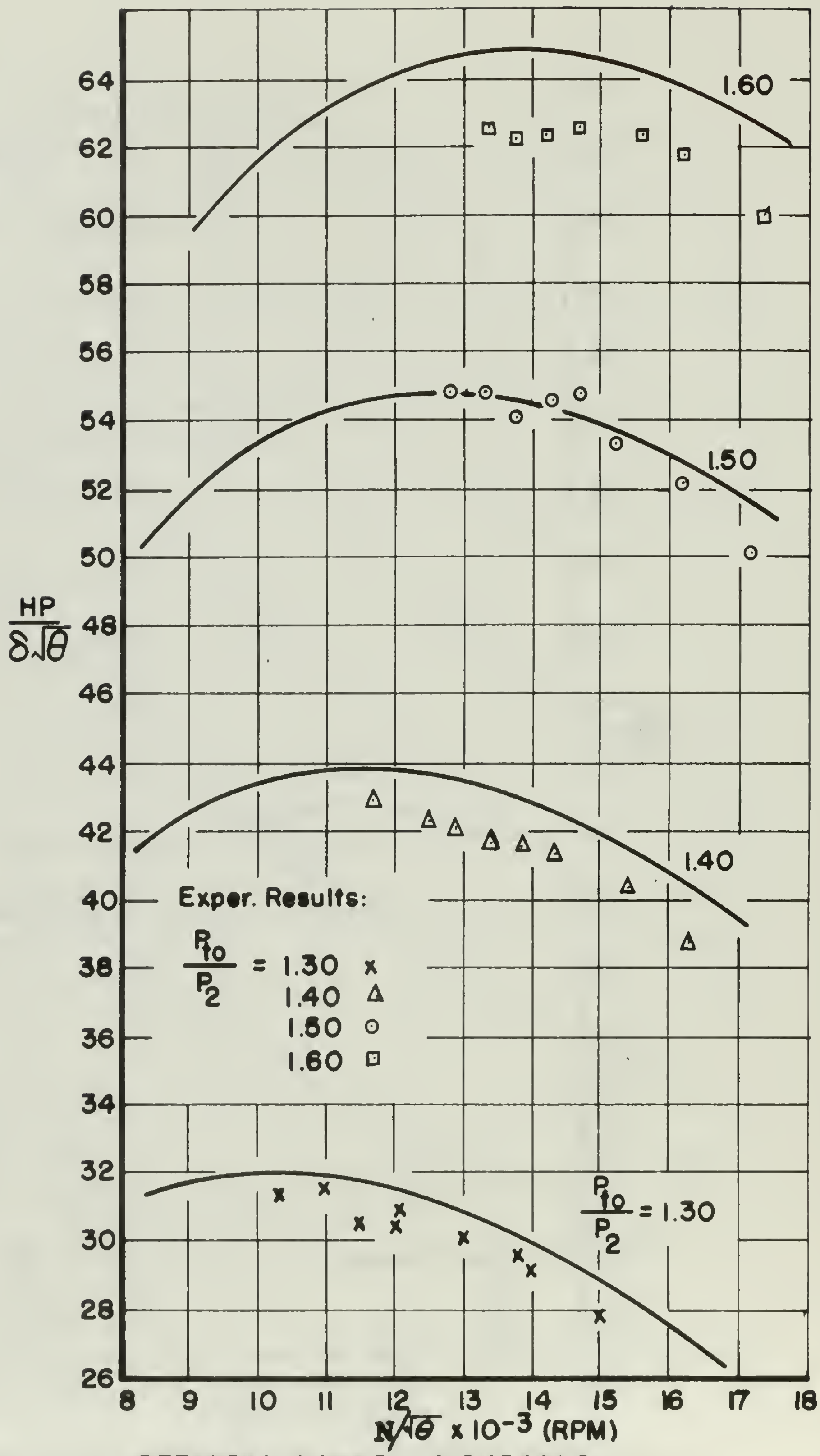
FIGURE 44



REFERRED POWER VS REFERRED RPM

$\Delta r = 0.033$ in. $\Delta x = 1.000$ in.

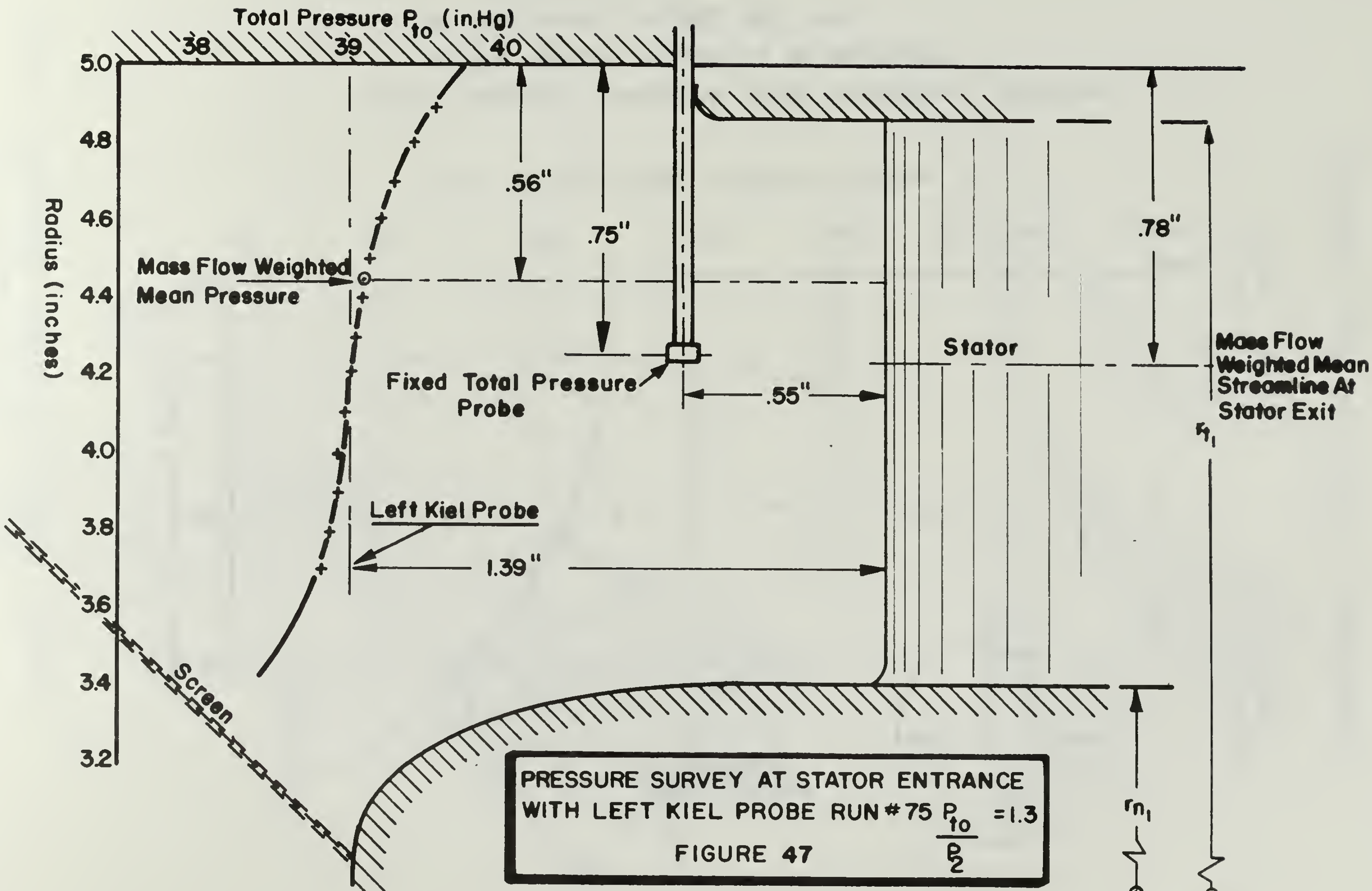
FIGURE 45



REFERRED POWER VS REFERRED RPM

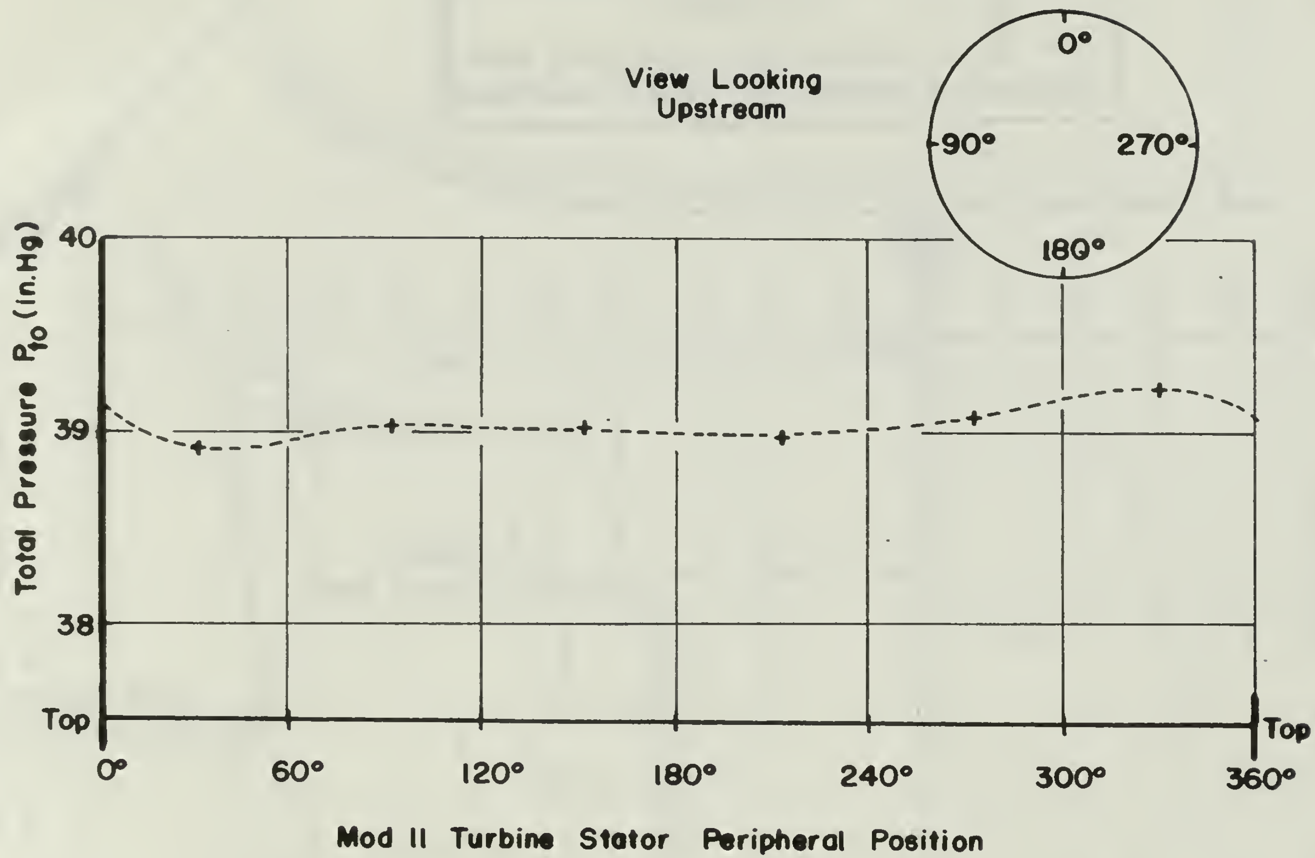
$\Delta r = 0.015$ in. $\Delta x = 1.000$ in.

FIGURE 46



PRESSURE SURVEY AT STATOR ENTRANCE WITH LEFT KIEL PROBE RUN # 75 $\frac{P_{to}}{P_2} = 1.3$

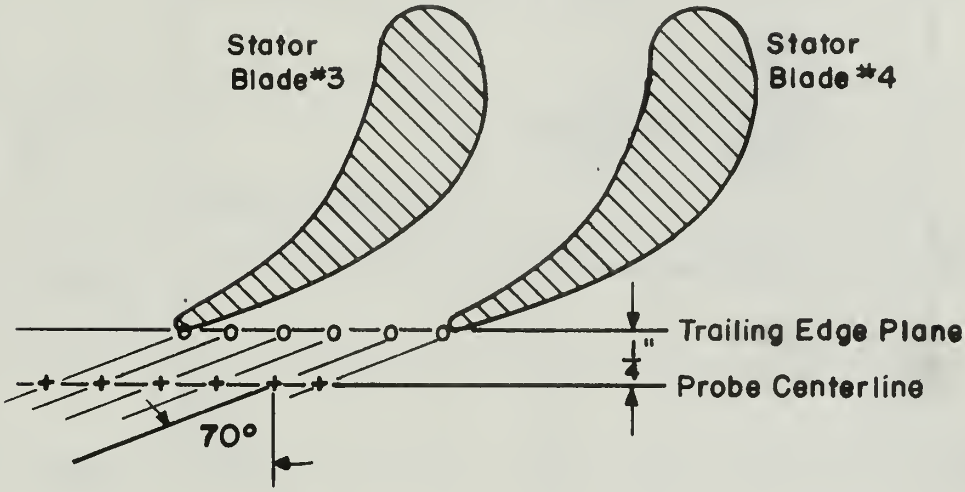
FIGURE 47

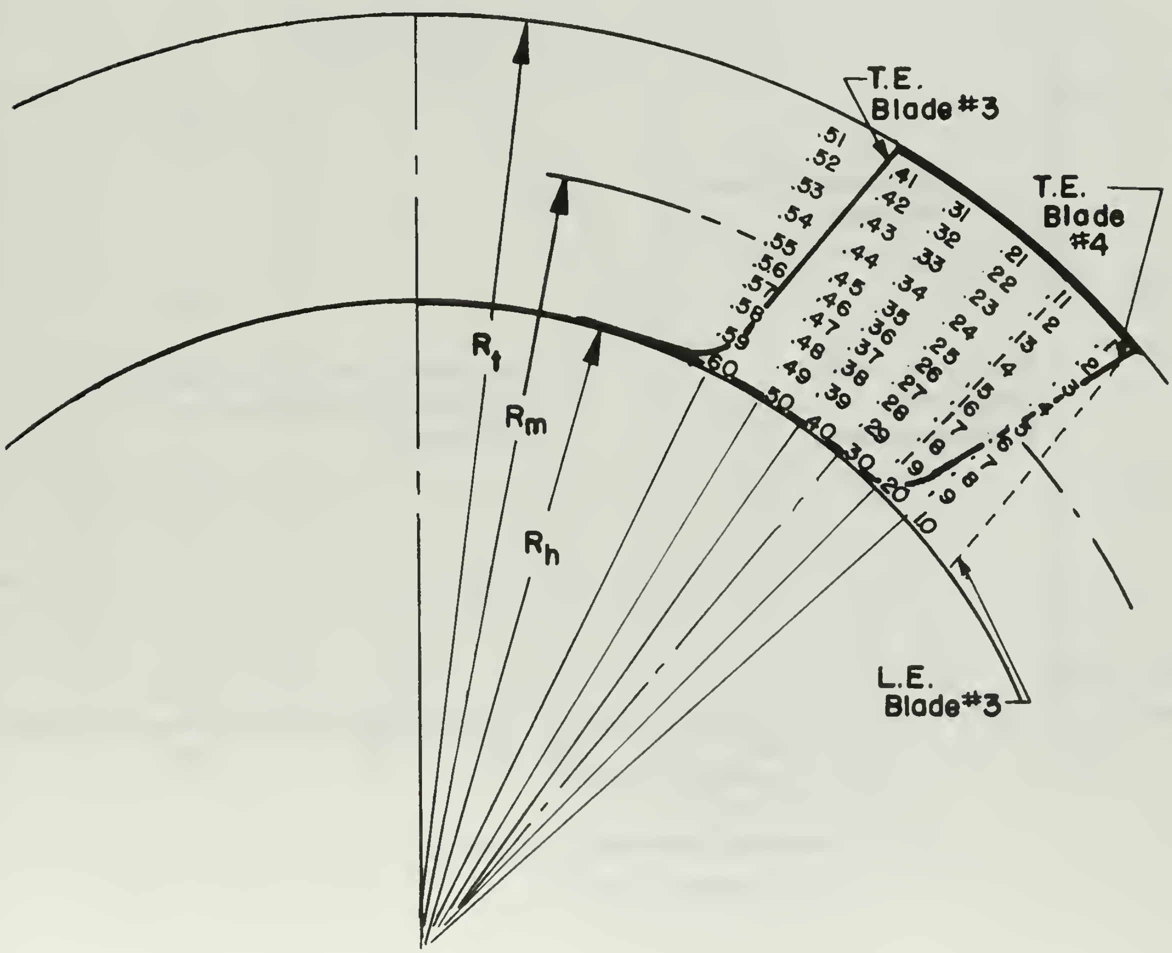


TOTAL PRESSURE VARIATION WITH PERIPHERAL POSITION
AT THE STATOR ENTRANCE AS MEASURED
BY THE FIXED PROBES RUN #75

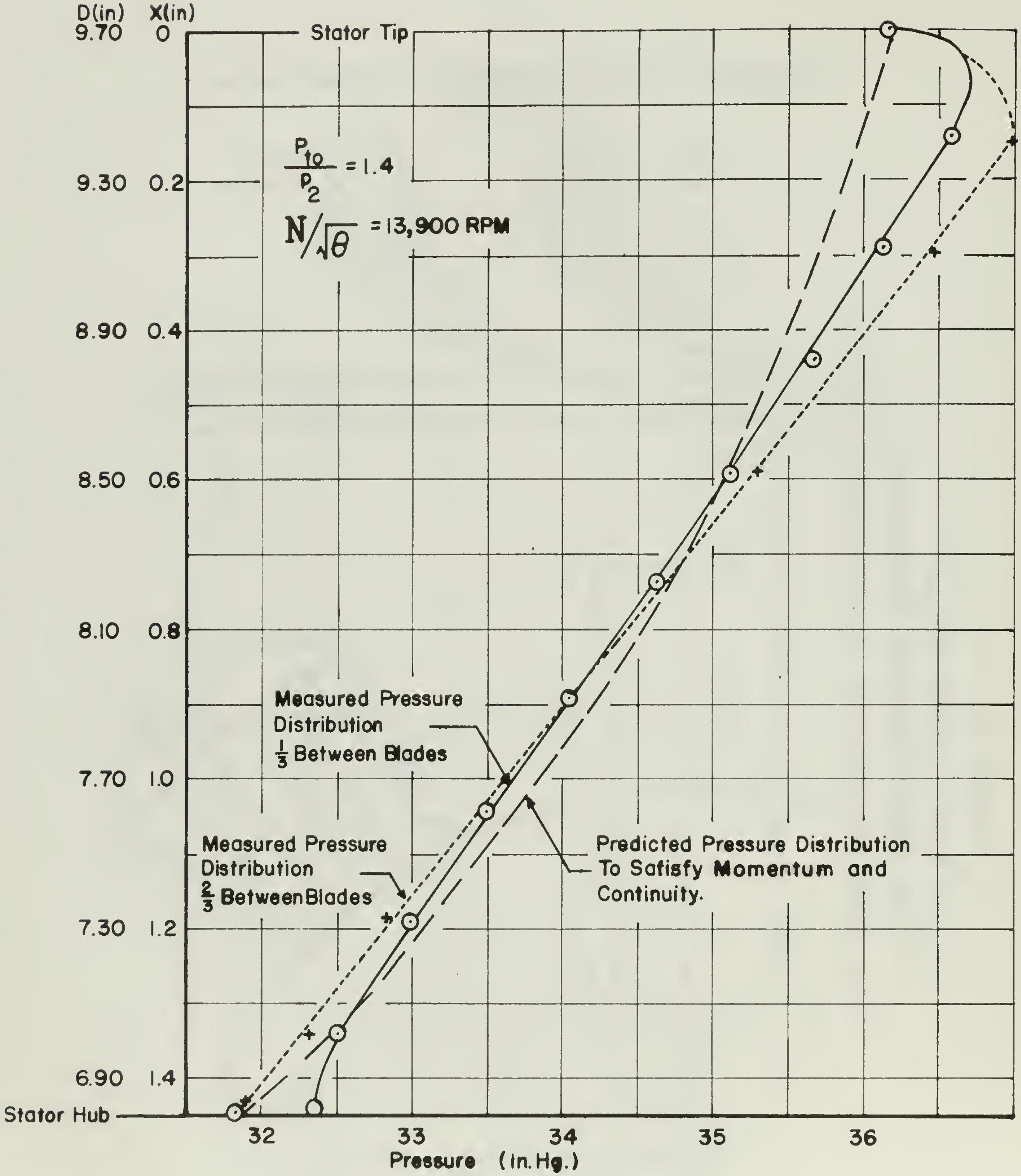
FIGURE 48

PRESSURE PROBE POSITIONING AT MEAN RADIUS
RUN #66



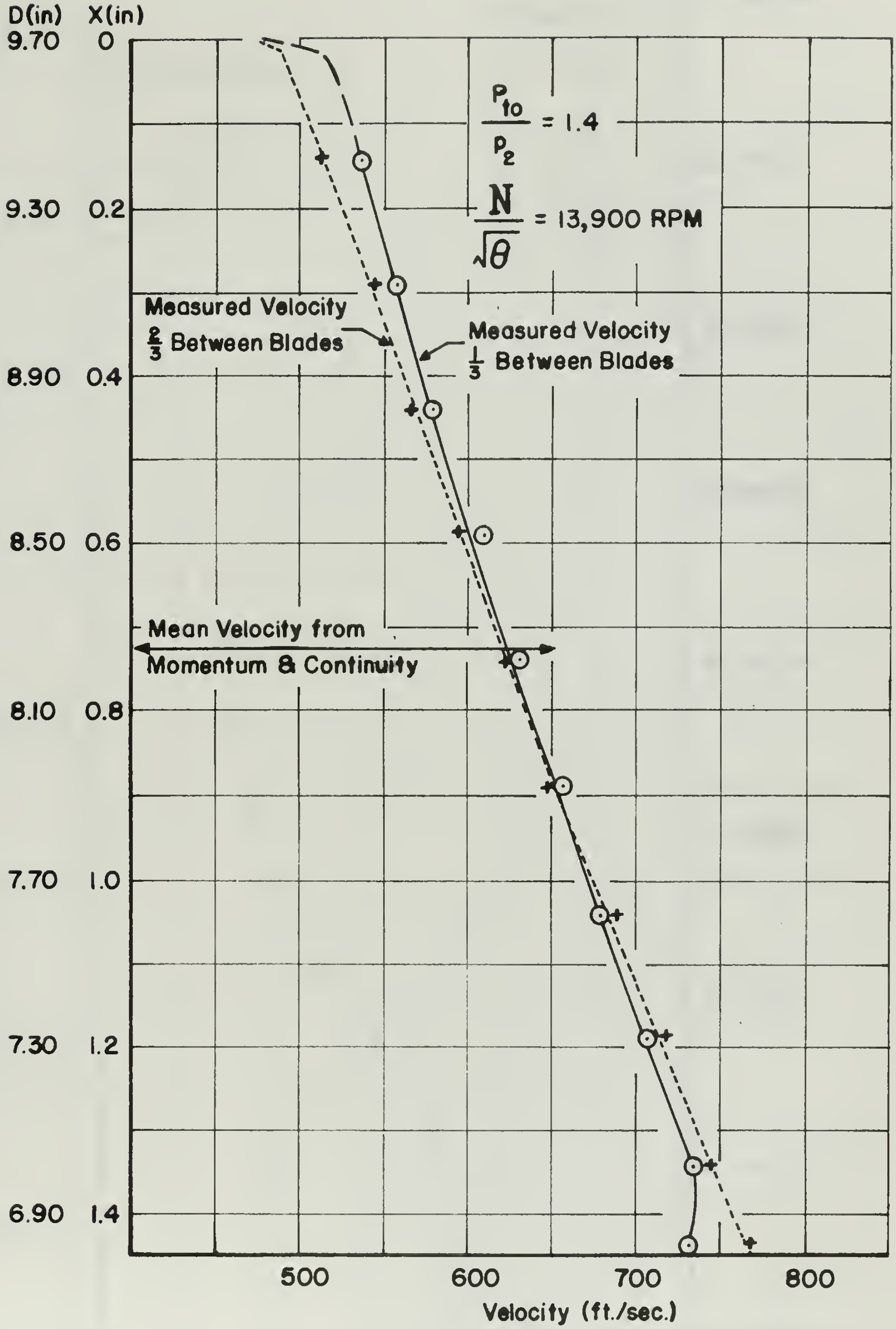


STATOR DISCHARGE PRESSURE SURVEY RUN #66
(Flow Probe DA-125 #926)
FIGURE 49



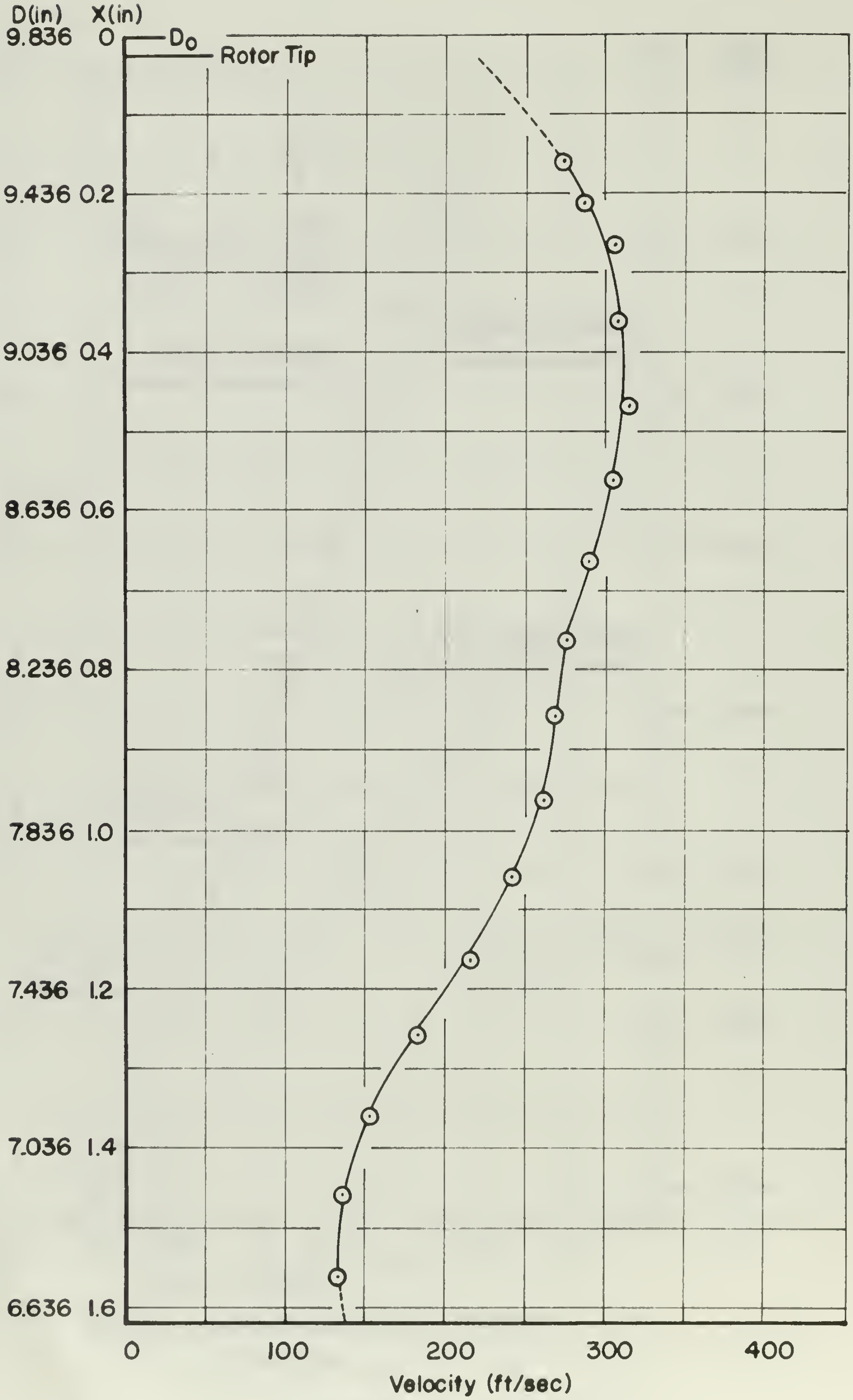
STATOR DISCHARGE SURVEY

FIGURE 50



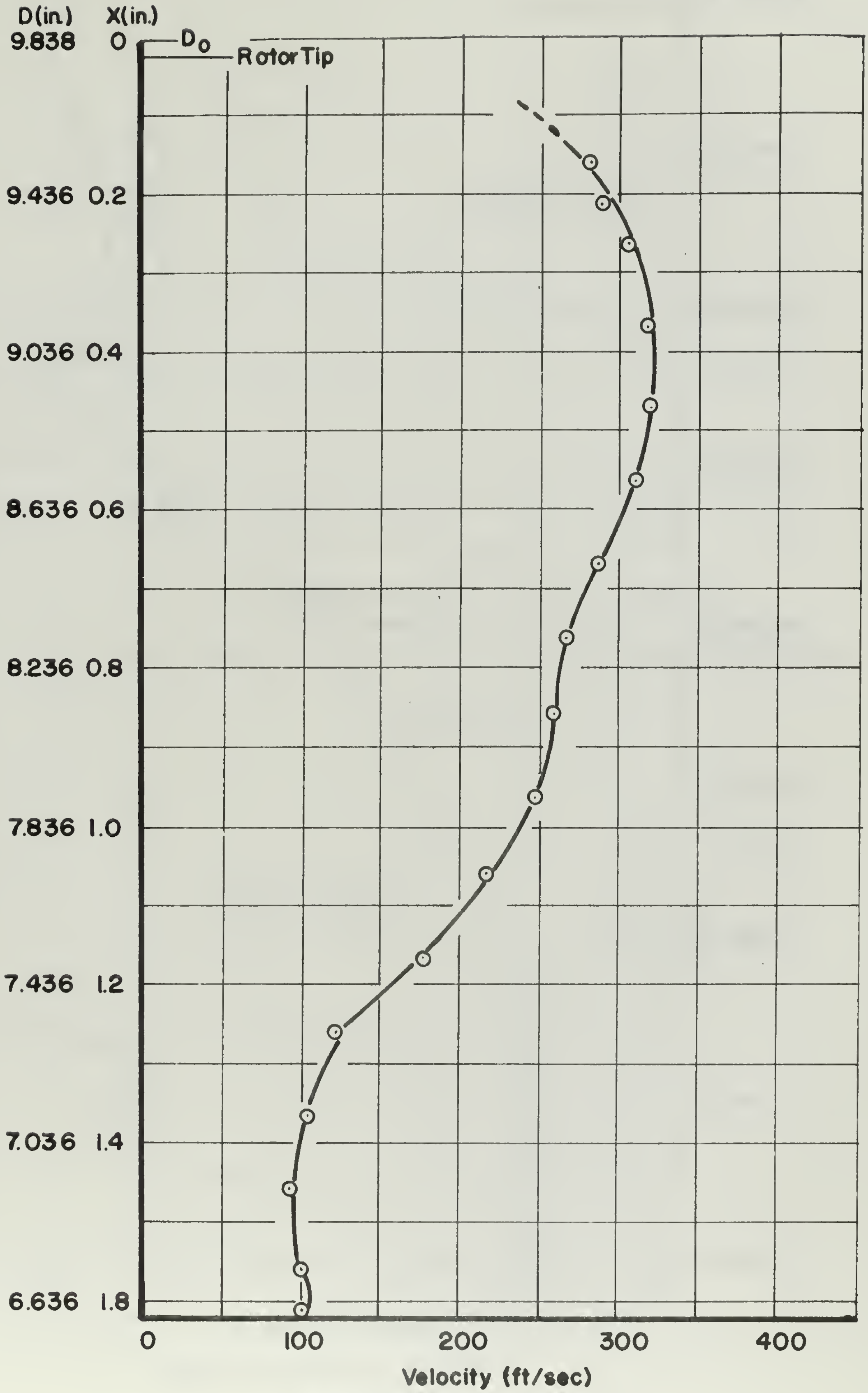
STATOR DISCHARGE SURVEY

FIGURE 51

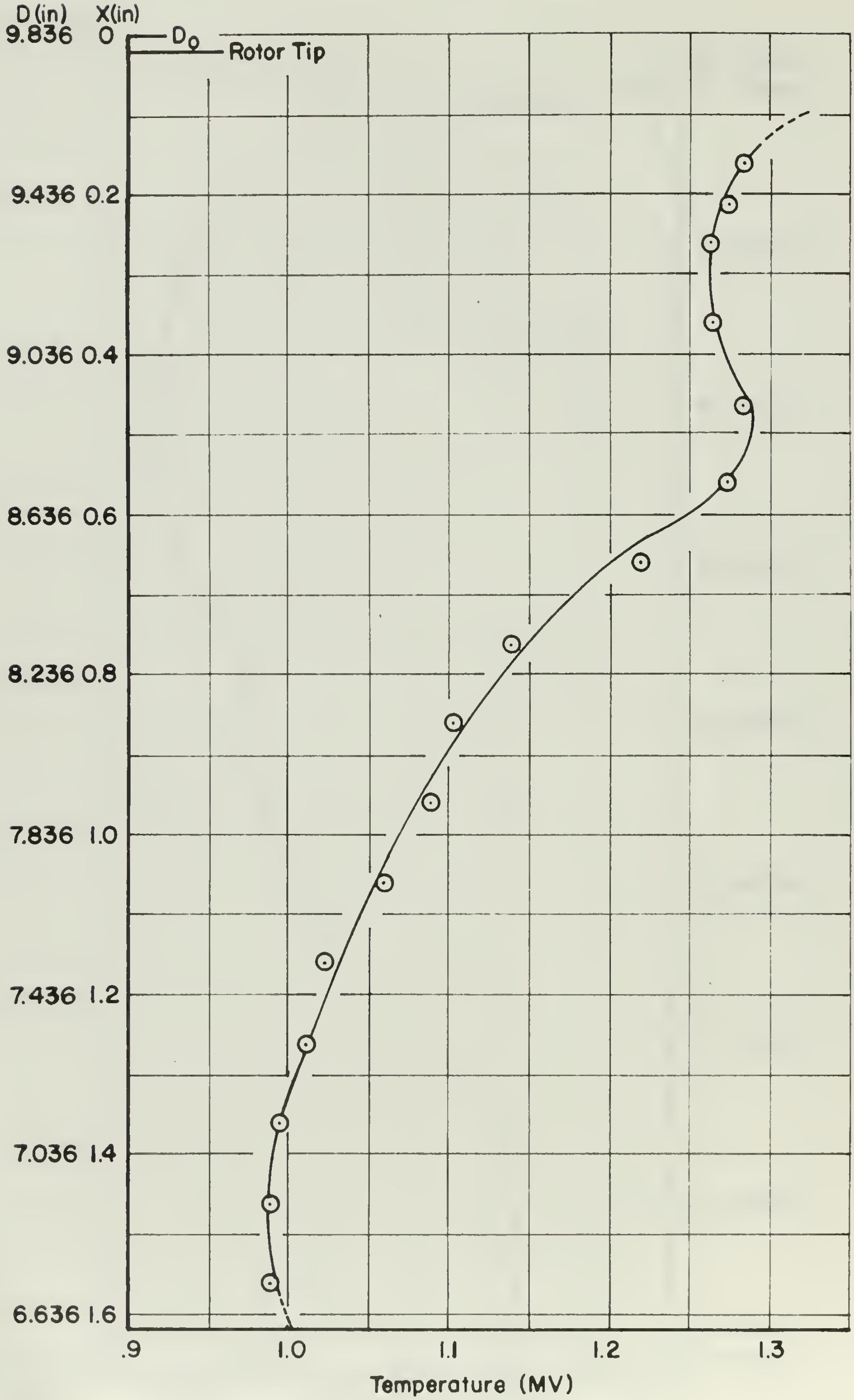


ROTOR DISCHARGE SURVEY

FIGURE 52

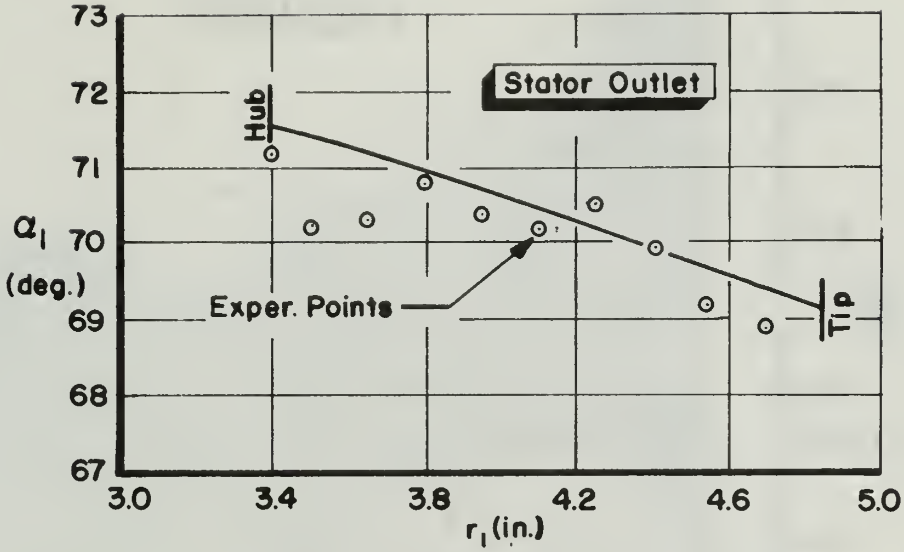


ROTOR DISCHARGE SURVEY
FIGURE 53



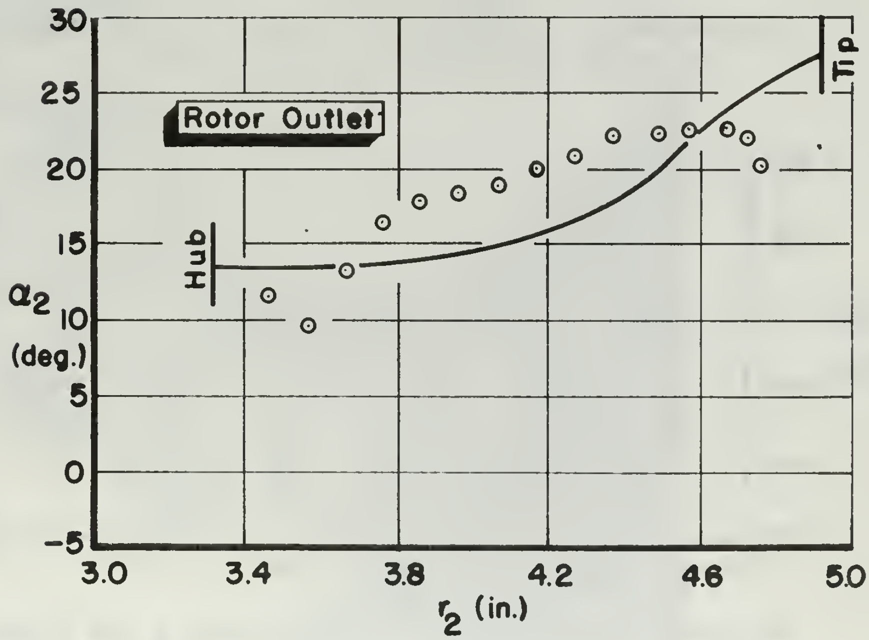
ROTOR DISCHARGE SURVEY

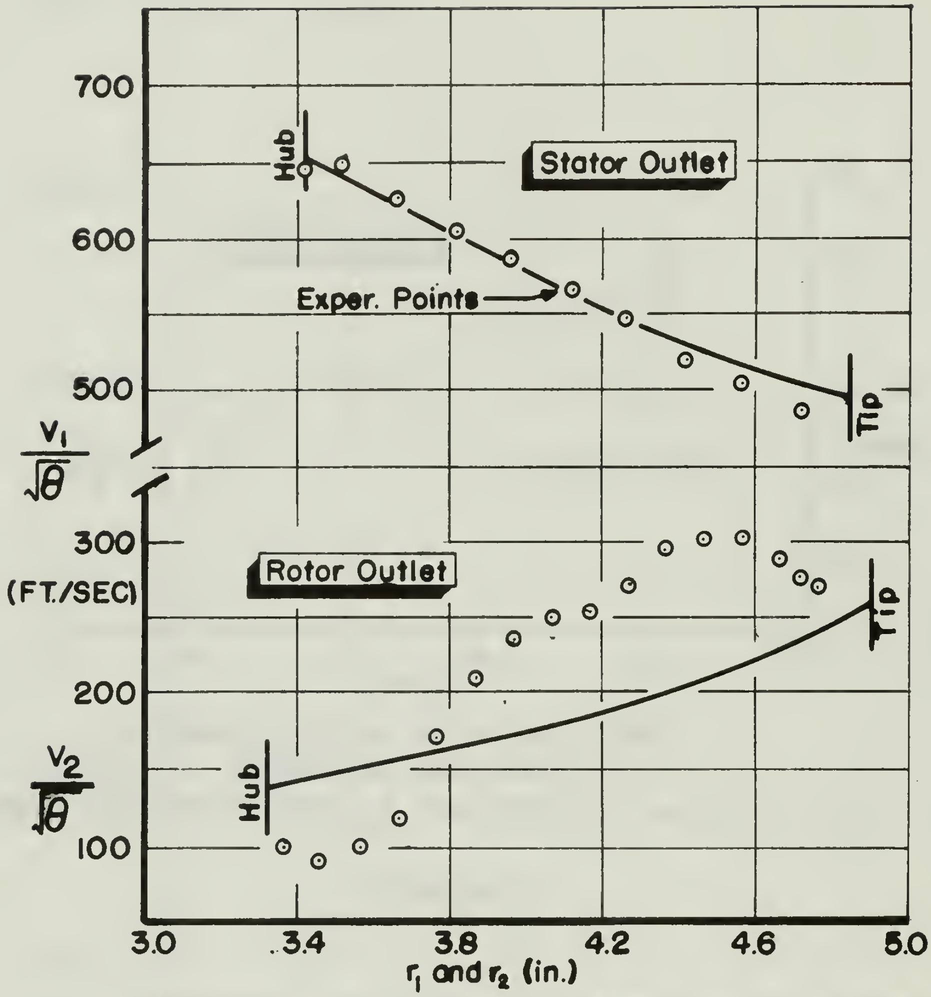
FIGURE 54



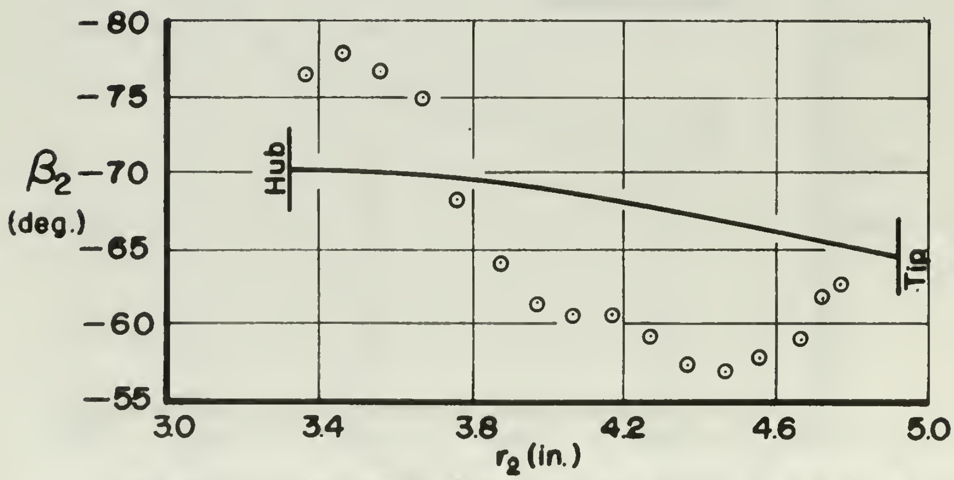
ABSOLUTE FLOW OUTLET ANGLES
AS FUNCTION OF RADIUS
($\Delta x = 1.000$ in., $\Delta r = 0.015$ in., $P_{to}/P_2 = 1.40$, RPM/$\sqrt{\theta} = 13{,}934$)

FIGURE 55





REFERRED VELOCITIES AS FUNCTION OF RADIUS
$\Delta r = 0.015''$, $P_{t0}/P_2 = 1.40$, $N/\sqrt{\theta} = 13,934$



RELATIVE ROTOR FLOW OUTLET ANGLE AS FUNCTION OF RADIUS ($\Delta r = 0.015''$, $P_{t0}/P_2 = 1.40$, $N/\sqrt{\theta} = 13,934$)

FIGURE 56

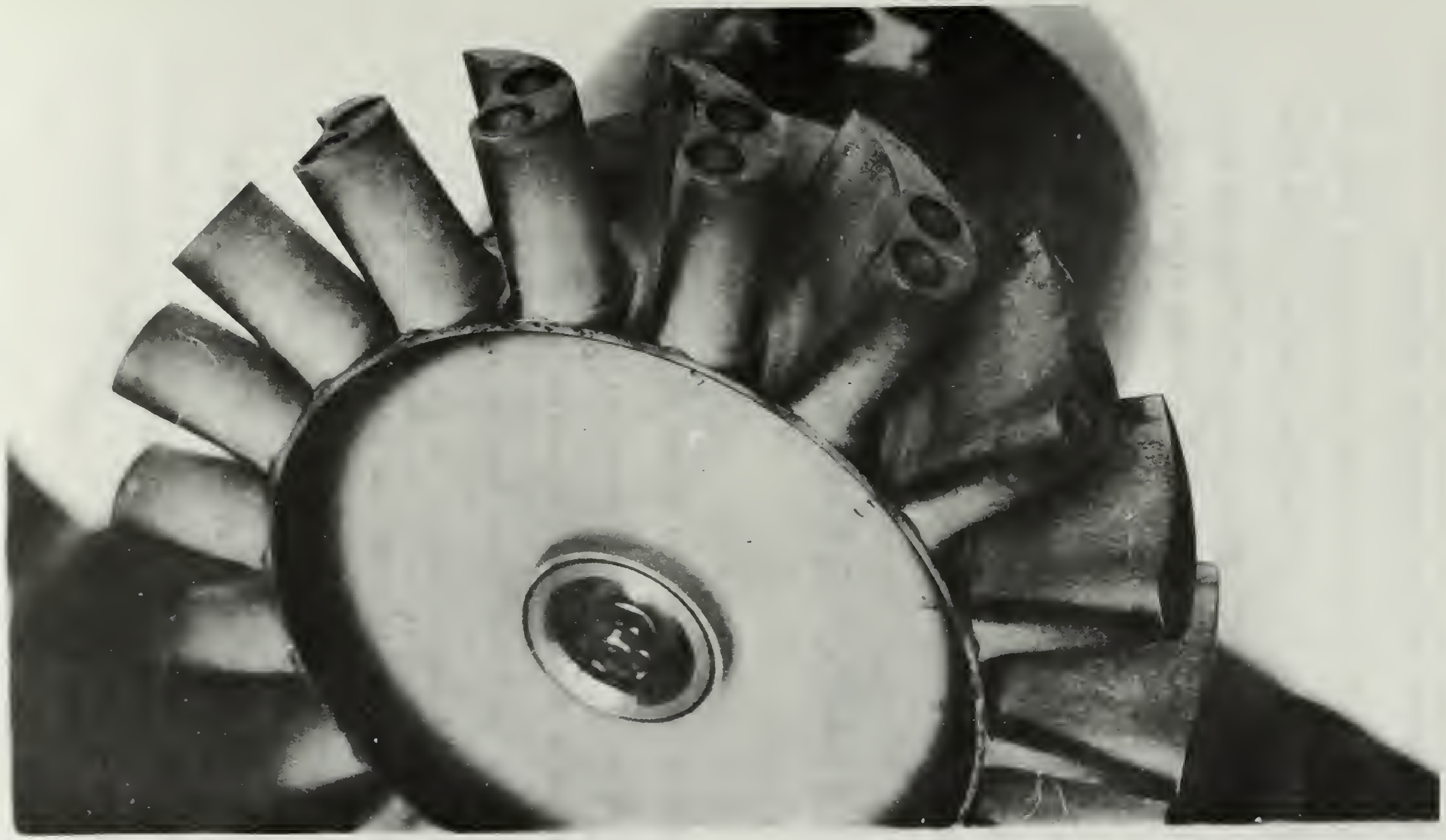


FIGURE 57

MOD II TURBINE ROTOR

APPENDIX I

FORMULA DEVELOPMENT FOR MEAN STREAMLINE ANALYSIS

A. The peripheral component of the velocity at the stator exit is determined by applying the moment of momentum equation to the fluid contained in the stator assembly. The assumed control volume surrounds the fluid in the assembly. It is assumed that significant flow separations do not exist, and the fluid shear stresses at the entrance and exit of the control volume are thus negligible (see Vavra[8]). With this assumption the moment of momentum equation may be written for this application as

$$\vec{M} = -\int_{s_0} \vec{r}_0 \times \vec{V}_0 \, d\dot{m}_{s_0} + \int_{s_1} \vec{r}_1 \times V_1 \, d\dot{m}_{s_1} \tag{66}$$

where

M = Moment applied to the control volume by the stator assembly.

S_o = Surface where fluid enters the control volume.

S_1 = Surface where fluid leaves the control volume.

The vector conventions for Eq. (66) are depicted on Fig. 13. Since net pressures which could produce moments on the stator assembly do not exist, pressure integrals have been omitted from Eq. (66).

In the axial direction the component of M is

$$\vec{M}_i = -\vec{J}\int_{s_0} r_0 V_{u0} \, d\dot{m}_{s_0} + \vec{J}\int_{s_1} r_1 V_{u1} \, d\dot{m}_{s_1} \tag{67}$$

---

[8] Vavra, M. H., Aero-Thermodynamics and Flow in Turbomachines. New York, London: John Wiley and Sons, Inc., 1960, p94.

The air enters the stator assembly from the plenum in a radial direction. Therefore the peripheral velocity component, V_{u_o}, is zero. Thus

$$M_i = \int_{S_1} r_1 V_{U_1} \, d\dot{m}_{S_1}$$

Since the average flow conditions are assumed to exist at the mean radius, Eq. (67) can be integrated to yield

$$M_i = R_m V_{U_1} \dot{m} \tag{68}$$

The moment applied to the inside of the shroud by the rotating fluid downstream of the stator exit is considered small. Thus, the moment applied to the fluid by the stator is the sum of the moment applied to the stator assembly by the stator assembly moment capsule, and the moment applied to the stator assembly by the closure plate; hence

$$M_i = M_s + M_{CL} \tag{69}$$

where

M_s = Moment applied to stator assembly by the stator assembly moment capsule. (ft-lb_f)

M_{CL} = Moment applied to stator assembly by the closure plate.

Substituting Eq. (69) into Eq. (68) and with $\dot{m} = \dot{W}/g$, there is

$$V_{U_1} = (M_s + M_{CL}) \; g / \dot{W} R_m \tag{70}$$

B. The axial velocity component at the stator exit is obtained by applying the conservation of momentum law to the same control volume as used above. For this application the momentum equation may be written as

$$\vec{F} = -\int_{S_0} \vec{V}_0 \, d\dot{m}_{S_0} + \int_{S_1} \vec{V}_1 \, d\dot{m}_{S_1} + \int_{S_0} (-\vec{n}_0) P_0 \, dS_0 - \int_{S_1} (-\vec{n}_1) P_1 \, dS_1 \tag{71}$$

where

F = Force applied to the fluid by the stator assembly. The vector field conventions are shown in Fig. 13.

Since neither $\vec{n}_o$ nor $\vec{V}_o$ have a component in axial direction, the vector component equation in the axial direction is

$$\vec{F}_i = t \int_{s_1} V_{a_1} \, d\dot{m}_{s_1} - t \int_{s_1} p_1 \, dS_1 \tag{72}$$

The pressure integral cannot be integrated unless the pressure distribution at the stator exit is known. The pressures at the tip and hub of the stator are recorded and the distribution is assumed to be linear. The static pressure at any radius, r, at the stator exit is therefore assumed to be

$$p_1 = p_h + \left(\frac{r - r_h}{r_t - r_h} \right) (p_t - p_h) \tag{73}$$

where

p_1 = Static pressure at radius, r, at the stator exit.

p_h = Static pressure at the stator hub.

p_t = Static pressure at the stator tip.

r_h = Radius at the stator hub.

r_t = Radius at the stator tip.

The pressure integral in Eq. (72) can now be integrated as

$$\int p_1 \, dS_1 = 2\pi \left[p_h/2 \, (r_t^2 - r_h^2) + \frac{p_t - p_h}{r_t - r_h} \left(\frac{r_t^3 - r_h^3}{3} - \frac{r_h r_t^2}{2} - \frac{r_h^3}{2} \right) \right] \tag{74}$$

and the velocity integral as

$$\int_{s_1} V_{a_1} \, d\dot{m}_{s_1} = V_{a_1} \dot{m} = V_{a_1} \dot{W}/g \tag{75}$$

The axial force applied to the fluid in the stator assembly is reacted to by the sum of the forces applied to the assembly by the axial force capsule, the closure plate, and the net pressures; that is,

$$F_i = F_s + F_{CL} + \Sigma F_p \tag{76}$$

where

F_s = Force applied to the stator assembly by the axial force capsule (lb_f)

F_{CL} = Force applied to the stator assembly by the closure plate (lb_f)

ΣF_p = Force applied to the stator assembly by the net pressure force (lb_f)

Figure 13 shows the applicable areas used in Eq. (77) for determining the net pressure force.

$$\Sigma F_p = -P_{hood} A_a + P_b A_b + P_c A_c + P_t A_e + P_h A_h \tag{77}$$

With Eqs. (74), (75), and (76); Eq. (72) is solved as

$$V_{a_1} = \Big\{ F_s + F + \Sigma F_p - 2\pi \Big[P_{h/2} (r_t^2 + r_h^2) + \frac{P_t - P_h}{r_t - r_h} \left(\frac{r_t^3 - r_h^3}{3} - \frac{r_h r_t^2}{2} - \frac{r_h^3}{2} \right) \Big] \Big\} g/\dot{W} \tag{78}$$

The thermodynamic properties of the fluid at the stator discharge and the performance parameters for the stator can now be calculated. Referring to Fig. 15, the static temperature is

$$T_1 = T_{t_0} - \frac{V_1^2}{2gJc_p} \quad ; \quad V_1^2 = V_{a_1}^2 + V_{u_1}^2 \tag{79}$$

From the equation of state the density is

$$\rho_1 = P_1 / R_G T_1 \tag{80}$$

The equation of continuity can now be checked as

$$\dot{W} = \rho_1 A_1 V_{a_1} \quad ; \quad A_1 = A_{ax} K_{te_1} \tag{81}$$

where

A_1 = Effective axial flow area at the stator exit.

A_{ax_1} = Actual axial flow area at the stator exit.

K_{te_1} = Factor to account for finite thickness of the stator blade trailing edges.

K_{te_1} is given by Vavra[9] from cascade data as

$$K_{te_1} = 1 - \frac{2.7}{10^3} \left(100 \, t_1/s_1\right)^{3.3} \quad a_1/s_1 \tag{82}$$

where the variables in Eq. (82) are shown in Fig. 7.

The axial velocity component at the stator exit may be obtained independently from the momentum methods mentioned previously by combining Eqs. (79), (80), and (81). First, the static temperature is obtained by combining Eqs. (79), (80), and (81). The resulting quadratic equation gives

$$T_1 = \frac{gJc_p A_1^2 P_1^2}{R_G^2 \dot{W}^2} \left\{ \left[1 - \frac{2\dot{W}^2 R_G^2}{gJc_p A_1^2 P_1^2} \left(\frac{V_{u_1}^2}{2gJc_p} - T_{t_0} \right) \right]^{1/2} - 1 \right\} \tag{83}$$

Using Eq. (79) the axial velocity component is found as

$$V_{a_1} = \left[2gJc_p (T_{t_0} - T_1) - V_{u_1}^2 \right]^{1/2} \tag{84}$$

[9]Vavra, M. H., Unpublished notes for course Ae 432, Naval Postgraduate School, 1966.

C. The peripheral component of the relative velocity at the rotor discharge is found by the application of the moment of momentum equation to the fluid contained between the rotor blades. With the same assumptions as used previously, the component of the relative moment of momentum equation in the axial direction is

$$\vec{M}_i = -\vec{J}\int_{s_1}(R_1 W_{u_1} + \omega R_1^2)\,d\dot{m}_{s_1} + \vec{J}\int_{s_2}(R_2 W_{u_2} + \omega R_2^2)\,d\dot{m}_{s_2} \quad (85)$$

where

M_i = Moment exerted on the fluid between the rotor entrance and exit.

The vector field conventions are shown in Fig. 17. Once again, the shear stresses at the entrance and exit surfaces are considered negligible. Therefore Eq. (85) is only valid when large separated flow conditions do not exist.

Substituting $\dot{W}/g$ for $\dot{m}$ and integrating

$$M_i = (W_{u_2} - W_{u_1})\, R_m \dot{W}/g \quad (86)$$

M_i is a negative quantity and is equal to the moment applied to the rotor shaft by the dynamometer, M_D, plus the moment absorbed by the rotor and dynamometer bearings. The bearing losses were calculated and found to be of the order of one-tenth of one percent of the power produced by the Mod II Turbine. Therefore, the bearing losses were ignored. Substituting M_D for $(-)M_i$ in Eq. (86) gives

$$W_{u_2} = W_{u_1} - gM_D/R_m\dot{W} \quad (87)$$

The relative axial component, W_{a2}, is determined by satisfying the equations of continuity and energy. The continuity equation is

$$\dot{W} = \rho_2 A_2 W_{a_2} \quad ; \quad A_2 = A_{ax} K_{te_2} \quad (88)$$

where

A_2 = Effective axial area at the rotor exit.

A_{ax_2} = Actual axial area at the rotor exit.

K_{te_2} = Factor to account for finite thickness of the rotor blades at the trailing edges.

Equation (82) must be modified slightly for the rotor because of rotor tip clearance effects. This is accomplished by assuming one-half of the area between the blade tips and the shroud to be the effective flow area of the tip clearance flow. K_{te_2} is then

$$K_{te_2} = \left\{1 - \frac{2.7}{10^3}\left(100\, t/s_2\right)^{3.3} a_2/s_2\right\}\left\{1 + \frac{\Delta r\, r_{t_2} + \Delta r^2/2}{(r_{t_2} - r_{h_2})^2}\right\} \tag{89}$$

where t_{e_2}, s_2, and a_2 are shown in Fig. 7 and where:

Δr = Radial clearance between the rotor tips and the shroud.

r_{t_2} = Tip radius of rotor blades.

r_{h_2} = Hub radius of rotor blades.

For the relative flow field, with no change of mean radius across the rotor, the energy equation can be written as

$$T_E = T_1 + W_1^2/2gJc_p = T_2 + W_2^2/2gJc_p \tag{90}$$

where

T_E = Equivalent temperature (see Fig. 15).

T_2 = Static temperature at the rotor exit.

W_2 = Relative velocity at the rotor exit.

Rearranging Eq. (90) and replacing W_2 by the components W_{a2} and W_{u2},

$$T_2 = T_1 + W_1^2/2gJc_p - W_{a_2}^2/2gJc_p - W_{u_2}^2/2gJc_p \tag{91}$$

where the unknowns are T_2 and W_{a2}.

By the equation of state

$$\rho_2 = p_2 / R_G T_2 \tag{92}$$

where

p_2 = Static pressure at the rotor exit = pressure in the test hood.

Combining Eqs. (88), (91), and (92) and solving for T_2 by the quadratic equation

$$T = \frac{gJc_p A_2^2 p_2^2}{2\dot{W}^2 R_G^2} \left\{ \left[1 - \frac{2\dot{W}^2 R_G^2}{gJc_p A_2^2 p_2^2} \left(\frac{W_{u2}^2}{2gJc_p} - T_1 - \frac{W_1^2}{2gJc_p} \right) \right]^{1/2} - 1 \right\} \tag{93}$$

Then by Eqs. (88) and (92)

$$W_{a_2} = \frac{\dot{W} R_G T_2}{p_2 A_2} \tag{94}$$

APPENDIX II

FORTRAN IV COMPUTER PROGRAM FOR PERFORMANCE DATA REDUCTION

A. Inputs

The input variables and their units are explained in comment statements in the executive program. The FORTRAN input statements are contained in Subroutine INPUT.

B. Outputs

Three output forms are included in the program.

1. A printout of the input variables is accomplished by Subroutine INPUT.

2. A printout of the general performance results is accomplished by Subroutine OUTPUTA.

3. A printout of the referred stage performance parameters is accomplished by Subroutine OUTPUT.

Samples of the last two output forms are contained in Appendix III.

```
      PROGRAM TTR2 1
C     COMPUTES EXPERIMENTAL PERFORMANCE CHARACTERISTICS OF THE
C     TURBINE TEST RIG
C     INPUT DATA DH(IN H2O),PNOZ(IN HG),TNOZ(MV),PTPL(IN HG),PHUB(IN HG)
C     PTIP(IN HG),PBP(IN HG),TTPL(MV),PATM(IN HG),RPM(RPM),TORQR(COUNTS)
C     AXIL(COUNTS),DYNAR(COUNTS),PHD(IN HG),PRF1(IN HG),PSPL(IN HG),
C     CLAXIL(COUNTS),CLTRQR(COUNTS),PRF2(IN HG),THD(MV),P14 THRU P17
C     (IN HG),TCL(DEGREES F),TCR(DEGREES F).
      DIMENSION DH(50),PNOZ(50),TNOZ(50),PTPL(50),PHUB(50),PTIP(50),
     1PBP(50),TTPL(50),PATM(50),RPM(50),TORQR(50),AXIL(50),DYNAR(50),
     2PHD(50),PRF1(50),PSPL(50),CLAXIL(50), CLTRQR(50),PRF2(50)
     3,P18(50),P15(50),P16(50),P17(50),P19(50),P20(50)
      DIMENSION FLOWT(50),PR(50),HP(50),XKIS(50),COEFL(50),COEFM(50),
     1COEFP(50),COEFS(50),V1(50),V2(50),W1(50),W2(50),U1(50),U2(50),
     2T1(50),T2(50),T2IS(50),TT2(50),ALPH1(50),ALPH2(50),BETA1(50),
     3BETA2(50),DBETA(50),ETA(50),ETAT(50),ZETAR(50),ZETAS(50),ZETA(50),
     4REACHB (50),REACMN(50),REACTP (50),VM1(50),WM1(50),PHI(50),
     5          XI(50),PRS(50)
      COMMON G,CR,C2,C3,RM1,RM2,AAX,ATH,QFLOWT,QTTPL,T1IS,QT1,QPTPL,
     1QPTIP,QPHUB,P1,QP18,QP15,QP16,QP17,QPRS,TORQ,CLTORQ,QV1,VA1,VU1,
     2QZETAS,QPHI,QXI,GAM,QALPH1,QBETA1,QRPM,QU1,QW1,QVM1,QWM1,QPHD,
     3 CLFAX,FAX,RTIP1,RHUB1,SKT,PAMB,QP19,QP20
      READ 20,MM
   20 FORMAT(I10)
      DO 99 M=1,MM
      CALL INPUT(NRUN,AXCLR,RADCLR,PBAR,N,TCL,TCR,DH,PNOZ,TNOZ,PTPL,
     1PHUB,PTIP,     TTPL,PATM,RPM,TORQR,AXIL,DYNAR,PHD,PRF1,PSPL,
     2CLAXIL,CLTRQR,PRF2,P18,P15,P16,P17,P19,P20)
      CALL SETCON(BETA,CN,DN,AAX,AAXR,ATH,CR,GAM,G,CP,CJ,C1,C2,C3,C4,
     1C5,RTIP1,RHUB1,RTIP2,RHUB2,RM1,RM2,RADCLR,SKT,RKT)
      DO 90 I=1,N
      QDH=DH(I)
      QPNOZ=PNOZ(I)
      QTNOZ=TNOZ(I)
      QPTPL=PTPL(I)
      QPHUB=PHUB(I)
      QPTIP=PTIP(I)
      QPBP=PBP(I)
      QTTPL=TTPL(I)
      QPATM=PATM(I)
      QRPM=RPM(I)
      QTORQR=TORQR(I)
      QAXIL=AXIL(I)
      QDYNAR=DYNAR(I)
      QPHD=PHD(I)
      QPRF1=PRF1(I)
      QPSPL=PSPL(I)
      QCLAXIL=CLAXIL(I)
```

```
QLTRQR=CLTRQR(I)
QPRF2=PRF2(I)
QP18=P18(I)
QP15=P15(I)
QP16=P16(I)
QP17=P17(I)
QP19=P19(I)
QP20=P20(I)
 CALL  CNVERT(QDH,QPNOZ,QTNOZ,QPTPL,QPHUB,QPTIP,      QTTPL,QPATM,
1QRPM,QTORQR,QAXIL,QDYNAR,QPHD,QPRF1,QPSPL, QLTRQR, QCLXIL,P1,P2,
2QP18,QP15,QP16,QP17,TORQ,CLTORQ,FAX,CLFAX,DYNA,PBAR,QPRF2,TCL,
3TCR,C5,PAMB,QP19,QP20)
 CALL FLORAT (CR,C5,DN,CN,BETA,QPNOZ,QPSPL,QTNOZ,QTTPL,QPHD,QDH,
1QFLOWT)
 CALL STATOR
 CALL ROTOR(G,CR,CP,CJ,C2,C3,RM1,RM2,AAXR,QFLOWT,QTTPL,QRPM,DYNA,
1QDP,P1,P2,QT1,QT2,QTT2,QT2IS,VA1,VU1,QV2,QW1,QW2,QU1,QU2,QALPH2,
2QBETA1,QBETA2,C4,RKT)
 CALL  PERFRM(G,CR,CP,C1,C2,C3,GAM,QTTPL,QPTPL,QPHUB,QPTIP,QPHD,
1QRPM,QFLOWT,DYNA,QDP,P2,T1IS,QT1,QT2IS,QPR,QETA,QXKIS,QCOEFL,
2QCOEFM,QCOEFP,QCOEFS, QEACMN,QEACHB ,QEACTP ,QZETAR,QALPH1,QALPH2,
3QBETA1,QBETA2,QDBETA,QHP,QU2,QW1,QW2)
 FLOWT(I)=QFLOWT
 PR(I)=QPR
 HP(I)=QHP
 XKIS(I)=QXKIS
 COEFL(I)=QCOEFL
 COEFM(I)=QCOEFM
 COEFP(I)=QCOEFP
 COEFS(I)=QCOEFS
 V1(I)=QV1
 V2(I)=QV2
 W1(I)=QW1
 W2(I)=QW2
 U1(I)=QU1
 U2(I)=QU2
 TTPL(I)=QTTPL
 T1(I)=QT1
 T2(I)=QT2
 T2IS(I)=QT2IS
 TT2(I)=QTT2
 ALPH1(I)=QALPH1
 ALPH2(I)=QALPH2
 BETA1(I)=QBETA1
 BETA2(I)=QBETA2
 DBETA(I)=QDBETA
 ETA(I)=QETA
 ZETAR(I)=QZETAR
```

```fortran
      ZETAS(I)=QZETAS
      REACHB (I)=QEACHB
      REACMN(I)= QEACMN
      REACTP (I)=QEACTP
      VM1(I)=QVM1
      WM1(I)=QWM1
      PHI(I)=QPHI
      XI(I)=QXI
      PRS(I)=QPRS
      PTPL(I)=QPTPL
   90 CONTINUE
      CALL OUTPTA (NRUN,AXCLR,RADCLR,FLOWT,PR,HP,XKIS,COEFL,COEFM,COEFP,
     1COEFS,V1,V2,W1,W2,U1,U2,T1,T2,T2IS,TT2,ALPH1,ALPH2,BETA1,BETA2,
     2DBETA,ETA,      ZETAR,ZETAS,      REACHB ,REACMN,REACTP ,VM1,WM1,
     3PHI,      XI,PRS,RPM,TTPL,N)
      CALL OUTPUT(NRUN,AXCLR,RADCLR,N,PR,XKIS,ETA,COEFL,COEFM,COEFP,
     1COEFS,REACHB ,REACTP ,PTPL)
   99 CONTINUE
      END
```

```
      SUBROUTINE INPUT(NRUN,AXCLR,RADCLR,PBAR,N,TCL,TCR,DH,PNOZ,TNOZ,     0115
     1PTPL,PHUB,PTIP,     TTPL,PATM,RPM,TORQR,AXIL,DYNAR,PHD,PRF1,PSPL,     0116
     2CLAXIL, CLTRQR,PRF2,P18,P15,P16,P17,P19,P20)
      DIMENSION DH(50),PNOZ(50),TNOZ(50),PTPL(50),PHUB(50),PTIP(50),        0118
     1          TTPL(50),PATM(50),RPM(50),TORQR(50),AXIL(50),DYNAR(50),     0119
     2PHD(50),PRF1(50),PSPL(50),CLAXIL(50), CLTRQR(50),PRF2(50),            0120
     3P18(50),P15(50),P16(50),P17(50),P19(50),P20(50)
      READ (5,101)NRUN                                                      0122
      READ (5,102)AXCLR,RADCLR                                              0123
      READ (5,102)PBAR                                                      0124
      READ (5,101)N                                                         0125
      READ (5,102)TCL,TCR                                                   0125A
      READ (5,102)(DH(I),I=1,N)                                             0126
      READ (5,102)(PRF1(I),I=1,N)                                           0127
      READ (5,102)(PTIP(I),I=1,N)                                           0128
      READ (5,102)(P15 (I),I=1,N)                                           0130
      READ (5,102)(P16 (I),I=1,N)                                           0131
      READ (5,102)(P17 (I),I=1,N)                                           0132
      READ (5,102)(P18 (I),I=1,N)                                           0129
      READ (5,102)(P19 (I),I=1,N)
      READ (5,102)(P20 (I),I=1,N)
      READ (5,102)(PRF2(I),I=1,N)                                           0133
      READ (5,102)(PTPL(I),I=1,N)                                           0134
      READ (5,102)(PATM(I),I=1,N)                                           0135
      READ (5,102)(PNOZ(I),I=1,N)                                           0136
      READ (5,102)(PSPL(I),I=1,N)                                           0137
      READ (5,102)(PHUB(I),I=1,N)                                           0138
      READ (5,102)(PHD (I),I=1,N)                                           0139
      READ (5,102)(TNOZ(I),I=1,N)                                           0140
      READ (5,102)(TTPL(I),I=1,N)                                           0141
      READ (5,102)(AXIL(I),I=1,N)                                           0142
      READ (5,102)(TORQR(I),I=1,N)                                          0143
      READ (5,102)(DYNAR(I),I=1,N)                                          0144
      READ (5,102)(RPM(I),I=1,N)                                            0145
      READ (5,102)(CLAXIL(I),I=1,N)                                         0146
      READ (5,102)(CLTRQR(I),I=1,N)                                         0147
      WRITE(6,105)NRUN,PBAR                                                 0148
      WRITE(6,107)(DH(I),I=1,N)                                             0149
      WRITE(6,107)(PRF1(I),I=1,N)                                           0150
      WRITE(6,107)(PTIP(I),I=1,N)                                           0151
      WRITE(6,107)(P15(I),I=1,N)                                            0153
      WRITE(6,107)(P16(I),I=1,N)                                            0154
      WRITE(6,107)(P17(I),I=1,N)                                            0155
      WRITE(6,107)(P18(I),I=1,N)                                            0152
      WRITE(6,107)(P19(I),I=1,N)
      WRITE(6,107)(P20(I),I=1,N)
      WRITE(6,107)(PRF2(I),I=1,N)                                           0156
      WRITE(6,107)(PTPL(I),I=1,N)                                           0157
```

```
      WRITE(6,107)(PHD(I),I=1,N)                                         0162
      WRITE(6,107)(TNOZ(I),I=1,N)                                        0163
      WRITE(6,107)(TTPL(I),I=1,N)                                        0164
      WRITE(6,107)(AXIL(I),I=1,N)                                        0165
      WRITE(6,107)(TCRQR(I),I=1,N)                                       0166
      WRITE(6,107)(DYNAR(I),I=1,N)                                       0167
      WRITE(6,107)(RPM(I),I=1,N)                                         0168
      WRITE(6,107)(CLAXIL(I),I=1,N)                                      0169
      WRITF(6,107)(CLTRQR(I),I=1,N)                                      0170
101   FCRMAT(I10)                                                        0173
102   FCRMAT(8F1C.4)                                                     0174
105   FCRMAT(1H1,//5X,11H RUN NUMBER,I5,//5X,40H INPUT DATA, CARD IMAGE,0175
     1 1 LINE = 1 CARD //,5X,6H PBAR=,F6.3/)                             0176
107   FCRMAT(8F15.5)                                                     0177
      RETURN                                                             0178
      END                                                                0179
```

```
      SUBROUTINE SETCON(BETA,CN,DN,AAX,AAXR,ATH,CR,GAM,G,CP,CJ,C1,C2,
     1C3,C4,C5,RTIP1,RHUB1,RTIP2,RHUB2,RM1,RM2,RADCLR,SKT,RKT)
      BETA=.533
      CN=1.05
      DN=4.25
      AAX=37.6499
      AAXR=41.7729
      ATH=12.70512
      CR=53.34
      GAM=1.401
      G=32.174
      CP=0.24
      CJ=778.16
      C1=2.*G*CJ
      C2=2.*G*CJ*CP
      C3=(GAM-1.)/GAM
      C4=1./C3
      C5=.0361269
      RTIP1=9.701/2.
      RHUB1=6.795/2.
      RTIP2=9.836/2.
      RHUB2=6.600/2.
      RM1=(RTIP1+RHUB1)/2.
      RM2=(RTIP2+RHUB2)/2.
      THKS=.048
      SSTAT=1.3637E
      ASTAT=.4635
      THKR=.048
      SROTR=1.4343
      AROTR=.540
      SKT=1.-(2.7/1000.)*(THKS/SSTAT*100.)**3.3*ASTAT/SSTAT
      RKT=(1.-(2.7/1000.)*(THKR/SROTR*100.)**3.3*AROTR/SROTR)*((AAXR+
     13.14159*RADCLR*(RTIP2+RADCLR/2.))/AAXR)
      RETURN
      END
```

```
      SUBROUTINE  CNVERT (DH,PNOZ,TNOZ,PTPL,PHUB,PTIP,    TTPL,PATM,RPM,0213A
     1TORQR,AXIL,DYNAR,PHD,PRF1,PSPL, CLTRQR,CLAXIL,P1,P2,P14,P15,P16,  0213B
     2P17,TORQ,CLTORQ,FAX,CLFAX,DYNA,PBAR,PRF2,TCL,TCR,C5,PAMB)         0214
      TEMP(X)=32.+35.98*X-.435*X**2                                      0216A
      GH2O=1.00013+TCR*.078/1000.-TCR**2.*.0014/1000.                    0215
      DH=DH*GH2O*C5                                                      0216
      CHGC=.49280-TCL*.5/10000.                                          0217
      PAMB=PBAR                                                          0217A
      PAMB=PAMB*CHGC                                                     0218
      CHGCR=.49280-TCR*.5/10000.                                         0219
      PNOZ=CHGCR*(PATM-PNOZ)+PAMB                                        0220
      PTPL=CHGCR*(PRF2-PTPL)+PAMB                                        0221
      PHUB=CHGCR*(PATM-PHUB)+PAMB                                        0222
      PTIP=CHGCR*(PRF1-PTIP)+PAMB                                        0223
      P14=CHGCR*(PRF1-P14)+PAMB                                          0224
      P15=CHGCR*(PRF1-P15)+PAMB                                          0225
      P16=CHGCR*(PRF1-P16)+PAMB                                          0226
      P17=CHGCR*(PRF1-P17)+PAMB                                          0227
      PSPL=CHGCR*(PATM-PSPL)+PAMB
      PHD=CHGCR*(PATM-PHD)+PAMB                                          0228A
      EPS=0.0                                                            0229
      P1=((PTIP+PHUB)/2.)*(1.+EPS)                                       0230
      P2=PHD                                                             0231
      TTPL= TEMP(TTPL)+459.7                                             0233
      TNOZ= TEMP(TNOZ)+459.7                                             0234
      TORQ=.3*TORQR/12.                                                  0235
      CLTORQ=.2207* CLTRQR/12.                                           0236
      FAX=.08*AXIL                                                       0237
      CLFAX=.1*CLAXIL                                                    0238
      DYNA=DYNAR/40.
      RETURN                                                             0244
      END                                                                0245
```

```
      SUBROUTINE FLORAT  (CR,C5,DN,CN,BETA,PNOZ,PSPL,TNOZ,TTPL,PHD,DH,    0246
     1FLOWT)                                                               0247
      ALPHN=1.+.00252*(TNOZ-527.7)/100.                                    0248
      Z=1.9+.24*((TNOZ-459.7)/100.-1.)                                     0249
      X=DH/PNOZ                                                            0250
      XR=1.-X                                                              0251
      B=(4.25/7.975)**4.                                                   0252
      Y=SQRT ((XR**(2./1.4))*3.5*(1.-XR**(.4/1.4))/(1.-XR)*(1.-B)/(1.      0253
     1-B*XR**(2./1.4)))                                                    0254
      FLOW=.8633*DN**2* ALPHN*CN*Y*SQRT (PNOZ*DH/TNOZ)                     0255
      PRL=PHD/PSPL                                                         0262
      FLOWS=SQRT ((1.-PRL)/4.0791)                                         0263
      FLOWL=.116*FLOWS*PSPL/SQRT (TTPL)                                    0264
      FLOWT=FLOW-FLOWL                                                     0265
      RETURN                                                               0266
      END                                                                  0267
```

```
      SUBROUTINE STATOR                                                    0268
      COMMON G,CR,C2,C3,RM1,RM2,AAX,ATH, FLOWT, TTPL,T1IS, T1, PTPL,       0268A
     1 PTIP, PHUB,P1, P18, P15, P16, P17, PRS,TORQ,CLTORQ, V1,VA1,VU1,     0269
     2 ZETAS, PHI, XI,GAM, ALPH1, BETA1, RPM, U1, W1, VM1, WM1, PHD,       0270
     3 CLFAX,FAX,RTIP1,RHUB1,SKT,PAMB,P19,P20                               0271
      PBAR=PAMB                                                            0271A
      CALL CONTIN(G,C2,AAX,RM1,PHD,PTIP,P1,PHUB,P18,P15,P16,P17,FLOWT,
     1TORQ,CLFAX,FAX,TTPL,VU1,VA1,V1,ALPH1,T1,RTIP1,RHUB1,CLTORQ,
     2RADCLR,PBAR,DELP1,C3,SKT,CR,P19,P20)
      PRS=P1/PTPL                                                          0272
      T1IS=TTPL*PRS**C3                                                    0273
      RAD=.10472*RPM                                                       0277
      U1=RM1*RAD/12.                                                       0278
      WU1=VU1-U1                                                           0279
      WA1=VA1                                                              0280
      BETA1=ATAN (WU1/WA1)                                                 0281
      W1=WA1/COS (BETA1)                                                   0282
      PHI=FLOWT/PTPL/ATH *SQRT (TTPL*CR/G)                                 0283
      XI=PHI /SQRT (2./C3*(PRS**(2./GAM)-PRS**((GAM+1.)/GAM)))             0284
      ZETAS=(T1-T1IS)/(TTPL-T1IS)                                          0286
      VM1=V1/SQRT (GAM*G*CR*T1)                                            0287
      WM1=W1/SQRT (GAM*G*CR*T1)                                            0288
      RETURN                                                               0289
      END                                                                  0290
```

```
      SUBROUTINE CCNTIN(G,C2,AAX,RM1,PHD,PTIP,P1,PHUB,P18,P15,P16,P17,
     1FLOWT,TORQ,CLFAX,FAX,TTPL,VU1,VA1,V1,ALPH1,T1,RTIP1,RHUB1,CLTORQ,
     2RADCLR,PBAR,CELP1,C3,SKT,CR,P19,P20)
      VU1=(TCRQ+CLTCRQ)*G/FLOWT/RM1*12.                               0293
      THETA2=VU1**2./C2/TTPL                                          0294
      AVA1=10000.
  997 SK=FLOWT/SKT/AAX*SQRT (CR/G*C3/2.*TTPL)/P1
      T1=TTPL*(SCRT (1.+4.*SK**2*(1.-THETA2))-1.)/2./SK**2            0296
      WRITE(6,995)T1
      V1=SQRT ((TTPL-T1)*C2)                                          0297
      WRITE(6,995)V1
      VA1=SQRT (V1**2 -VU1**2 )                                       0298
      WRITE(6,995)VA1
      IF (ABS(AVA1-VA1)-1.000)999,999,998
  998 PI=3.14159
      AVA1=VA1
      A1=PI/4.*11.C**2                                                0291
      WRITE(6,995)A1
      A2=A1-PI/4.*10.132**2
      WRITE(6,995)A2
      A2A=A1-A2-PI/4.*9.932**2
      WRITE(6,995)A2A
      A3=A1-PI/4.*(9.836+2.*RADCLR)**2.-A2-A2A                        0291B
      WRITE(6,995)A3
      A4=A1-A2-PI*RTIP1**2-A3-A2A                                     0291C
      WRITE(6,995)A4
      A6=PI*RHUB1**2                                                  0291D
      WRITE(6,995)A6
      F1=A1*PHD                                                       0292
      WRITE(6,995)F1
      F2=A2*(P19+P20)/2.
      WRITE(6,995)F2
      F2A=A2A*(P17+P18)/2.
      WRITE(6,995)F2A
      F3=A3*(P15+P16)/2.
      WRITE(6,995)F3
      F4=A4*PTIP                                                      0295
      WRITE(6,995)F4
      F6=A6*PHUB                                                      0297
      WRITE(6,995)F6
      FNET=F1-F2-F3-F4-F6+CLFAX+FAX-F2A
      WRITE(6,995)FNET
      F5=FNET-(AVA1*FLCWT/G)
      WRITE(6,995)F5
      EPS=(F5*3./PI-PHUB*(RTIP1**2+RTIP1*RHUB1-2.*RHUB1**2)-PTIP*(2.*
     1RTIP1**2-RHUB1*RTIP1-RHUB1**2))/((PHUB+PTIP)*(RTIP1**2-RHUB1**2))
      WRITE(6,995)EPS
      P1=((PTIP+PHUB)/2.)*(1.+EPS)
```

```
      SUBROUTINE ROTOR(G,CR,CP,CJ,C2,C3,RM1,RM2,AAXR,FLOWT,TTPL,RPM,         0303
     1DYNA,DP,P1,P2,T1,T2,TT2,T2IS,VA1,VU1,V2,W1,W2,U1,U2,ALPH2,BETA1,       0304
     2BETA2,C4,RKT)                                                          0305
      RAD=.10472*RPM                                                         0306
      DP=DYNA*RAD/CJ                                                         0307
      VU2=RM1/RM2*VU1-DYNA*G/RM2/FLOWT*12.                                   0308
      TT2=TTPL-DP/CP/FLOWT                                                   0309
      T2IS=T1*(P2/P1)**C3                                                    0310
      U2=RM2*RAD/12.                                                         0311
      WU2=VU2-U2                                                             0311A
      TE=T1+(W1**2.-U1**2.+U2**2.)/C2                                        0312
      TETA2=(WU2**2 )/TE/C2                                                  0313
      RK=FLOWT/RKT/AAXR*SQRT (CR/G*C3/2.*TE)/P2                              0314
      T2=TE*(SQRT (1.+4.*RK**2.*(1.-TETA2))-1.)/2./RK**2.                    0315
      V2=SQRT ((TT2-T2)*C2)                                                  0316
      VA2=SQRT(V2**2-VU2**2)                                                 0317
   15 WA2=VA2                                                                0318
      W2=SQRT (WA2**2+WU2**2)                                                0320
      ALPH2=ATAN (VU2/VA2)                                                   0321
      BETA2=ATAN (WU2/WA2)                                                   0322
      RETURN                                                                 0323
      END                                                                    0324
```

```
      SUBROUTINE PERFRM  (G,CR,CP,C1,C2,C3,GAM,TTPL,PTPL,PHUB,PTIP,PHD,
     1RPM,FLOWT,DYNA,DP,P2,T1IS,T1,T2IS,PR,ETA,XKIS,COEFL,COEFM,COEFP,
     2COEFS,REACMN,REACHB ,REACTP ,ZETAR,ALPH1,ALPH2,BETA1,BETA2,DBETA,
     3HP,U2,W1,W2)
      PR=PTPL/P2
      T2TH=TTPL*(PHD/PTPL)**C3
      DHIS=CP*(TTPL-T2TH)
      ETA=DP/DHIS/FLOWT
      XKIS=DHIS*C1/U2**2
      XKIS=XKIS*4.2048**2/4.125**2
      DEL=PTPL/14.69
      THETA=SQRT (GAM*CR*TTPL)/196.8107
      COEFL=FLOWT*THETA/DEL
      COEFM=DYNA/DEL
      HP=3600./2545.*DP
      COEFP=HP/(DEL*THETA)
      COEFS=RPM/THETA
      REACMN=1.0-CP*(TTPL-T1IS)/DHIS
      REACHB =((PHUB/PHD)**C3-1.)/((PTPL/PHD)**C3-1.)
      REACTP =((PTIP/PHD)**C3-1.)/((PTPL/PHD)**C3-1.)
      SQW2TH=C2*(T1-T2IS)+W1**2
      ZETAR=1.-W2**2/SQW2TH
      ALPH1=ALPH1*57.295779
      ALPH2=ALPH2*57.295779
      BETA1=BETA1*57.295779
      BETA2=BETA2*57.295779
      DBETA=BETA1-BETA2
      RETURN
      END
```

```
      SUBROUTINE OUTPT4 (NRUN,AXCLR,RADCLR,FLOWT,PR,HP,XKIS,COEFL,COEFM,0354
     1COEFP,COEFS,V1,V2,W1,W2,U1,U2,T1,T2,T2IS,TT2,ALPH1,ALPH2,BETA1,    0355
     2BETA2,DBETA,ETA,      ZETAR,ZETAS,       REACHB ,REACMN,REACTP ,   0356
     3VM1,WM1,PHI,       XI,FRS,RPM,TTPL,N)                              0357
      DIMENSION FLOWT(50),PR(50),HP(50),XKIS(50),COEFL(50),COEFM(50),    0358
     1COEFP(50),COEFS(50),V1(50),V2(50),W1(50),W2(50),U1(50),U2(50),     0359
     2T1(50),T2(50),T2IS(50),TT2(50),ALPH1(50),ALPH2(50),BETA1(50),      0360
     3BETA2(50),DBETA(50),ETA(50),ETAT(50),ZETAR(50),ZETAS(50),ZETA(50),0361
     4REACHB (50),REACMN(50),REACTP (50),VM1(50),WM1(50),PHI(50),        0362
     5          XI(50),FRS(50),RPM(50),TTPL(50)                          0363
      WRITE(6,805)                                                       0364
  805 FORMAT(1H1//22H ARES TURBINE MODEL II //)                          0365
      WRITE(6,806)NRUN,AXCLR,RADCLR                                      0366
  806 FORMAT(11H RUN NUMBER I3,8H SPACING F10.3,11H TIP CLEAR. F10.3/)      0322
      WRITE(6,807)                                                       0323
  807 FORMAT (5X,6H POINT  6X,10H FLOW RATE  9X,4H RPM                      0324
    1 5X,15H PRESSURE RATIO    5X,11H HORSEPOWER  /)                        0325
      DO 808 I=1,N                                                          0326
  808 WRITE(6,809)I,FLOWT(I),RPM(I),PR(I),HP(I)                          0327
  809 FORMAT (I5,12X,4(F10.4,5X))                                           0328
      WRITE(6,810)                                                       0329
  810 FORMAT(///20X,37H DIMENSIONLESS PERFORMANCE PARAMETERS //             0330
     15X, 6H POINT 11X, 2H K 10X, 9H REFERRED  8X, 9H REFERRED              0331
     27X,9H REFERRED  7X,9H REFERRED  6X,        /                          0332
     317X,11H ISENTROPIC  5X,10H FLOW RATE  8X, 7H TORQUE                   0333
     4 9X, 6H POWER 10X, 6H SPEED  9X,/)                                    0334
      DO 811 I=1,N                                                          0335
  811 WRITE(6,812)     I,XKIS(I),COEFL(I),COEFM(I),COEFP(I),COEFS(I)     0336
  812 FORMAT ( I5,12X,6(F10.4,6X))                                          0337
      WRITE(6,813)NRUN                                                   0338
  813 FORMAT(1H1/////5X,16H GENERAL RESULTS //20X,20H VELOCITIES (FT/SEC)   0339
     1)/,20X,11H RUN NUMBER     I5/                                         0340
     2//5X, 6H POINT 10X, 3H V1 12X, 3H V2 12X,3H W1 12X,3H W2              0341
     312X,3H U1 12X,3H U2  /  )                                             0342
      DO 814 I=1,N                                                          0343
  814 WRITE(6,815)   I,V1(I),V2(I),W1(I),W2(I),U1(I),U2(I)               0344
  815 FORMAT ( I5,12X, 6(F10.5,5X))                                         0345
      WRITE(6,816)                                                       0346
  816 FORMAT (       /20X,23H TEMPERATURES (DEG R )  //                     0347
    1 5X, 6H POINT    8X, 7H PLENUM  6X, 7H STATOR  8X, 6H ROTOR            0348
    2 9X,11H ISENTROPIC   4X, 6H TOTAL  /19X, 6H TOTAL  7X,                 0349
     310H DISCHARGE  5X,10H DISCHARGE  5X, 8H FROM T1  7X,                  0350
     410H DISCHARGE / )                                                     0351
      DO 817 I = 1,N                                                        0352
  817 WRITE(6,818)       I, TTPL(I), T1(I), T2(I), T2IS(I), TT2(I)       0353
  818 FORMAT ( I5,12X, 5(F10.5,5X))                                         0354
      WRITE(6,819)NRUN                                                   0355
  819 FORMAT(1H1/////20X,33H FLOW ANGLES (DEGREES FROM AXIAL)  //           0356
```

```
   120X,11H RUN NUMBER     I5///
   2 5X, 6H POINT    7X, 8H ALPHA 1  8X, 8H ALPHA 2  7X, 7H BETA 1
   3 8X, 7H BETA 2   6X,12H DELTA BETA  / )
    DO 820 I=1,N
820 WRITE(6,821) I, ALPH1(I),ALPH2(I),BETA1(I),BETA2(I),DBETA(I)
821 FORMAT ( I5,12X, 5(F10.5,5X))
    WRITE(6,822)
822 FORMAT (      ///20X,24H EFFICIENCIES AND LOSSES     //
   12X,6H POINT 10X, 11H EFFICIENCY 17X, 5H ZETA 20X, 5H ZETA/
   217X, 13H TOTAL STATIC 16X, 6H ROTOR 18X, 7H STATOR/)
    DO 823 I=1,N
823 WRITE(6,824)   I,ETA(I),ZETAR(I),ZETAS(I)
824 FORMAT (I5,12X,3(F10.5,15X))
    WRITE(6,825)NRUN
825 FORMAT  (1H1,36H MACH NUMBERS AND DEGREE OF REACTION    //
   120X,11H RUN NUMBER     I5///
   25X,6H POINT  8X,9H REACTION  6X,9H REACTION  7X,9H REACTION
   37X,9H ABSOLUTE  7X,9H RELATIVE  / 23X,4H HUB  9X,5H MEAN  11X,
   44H TIP  12X,7H MACH 1  9X,7H MACH 1    //)
    DO 826 I=1,N
826 WRITE(6,827) I,REACHB (I),REACMN(I),REACTP (I),VM1(I),WM1(I)
827 FORMAT  (I5,12X,5(F10.4,6X))
    WRITE(6,828)
828 FORMAT (//49H STATOR PRESSURE RATIO AND THROAT BLOCKAGE FACTOR//
   12X,6H POINT 11X,9H PRESSURE 17X,9H BLOCKAGE /
   221X,6H RATIO 19X,7H FACTOR /)
    DO 829 I=1,N
829 WRITE(6,830) I,PRS(I),XI(I)
830 FORMAT(I5,12X,2(F10.5,15X))
    RETURN
    END
```

```
      SUBROUTINE OUTPUT(NRUN,AXCLR,RADCLR,N,PR,XKIS,EFF,COEFL,COEFM,
     1                  COEFP,COEFS,REACHB ,REACTP ,PTPL)
      DIMENSION PR(50),XKIS(50),EFF(50),COEFL(50),COEFM(50),COEFP(50),
     1          COEFS(50),REACHB (50),REACTP (50),PTPL(50),NPTS(8),
     2          NPTSS(8),ICOEFS(50)
      READ(5,905)DATE
      READ(5,906)  REPRTA ,REPRTB ,TTYPEA,TTYPEB,CONFIG,METHOD
      READ(5,907)RMEAN
      READ(5,908)J
      READ(5,909)  (NPTS(K),NPTSS(K),K=1,8)
      DO 919 I=1,N
  919 EFF(I)=100.*EFF(I)
      DO 950 JJ=1,2
      IF  (N+3*J-43) 920,920,921
  920 NPP=1
      NXX=N
      GO TO 922
  921 NPP=2
      NXX=43
  922 NP=1
      NX=1
      K=1
  923 WRITE(6,900)  REPRTA ,REPRTB ,NP,NPP,TTYPEA,TTYPEB,CONFIG,RADCLR,
     1              AXCLR,NRUN,DATE,METHOD
      WRITE(6,901)RMEAN
      DO 940 I=NX,NXX
      ICOEFS(I)=COEFS(I)
      II=I
      WRITE(6,902)  I,PR(I),XKIS(I),EFF(I),COEFL(I),COEFM(I),COEFP(I),
     1              ICOEFS(I),REACHB (I),REACTP (I)
      IF  (J-K) 940,924,924
  924 IF  (I-NPTSS(K)) 940,925,940
  925 LL=NPTS(K)
      LLL=NPTSS(K)
      INTGER =LLL-LL+1
      AVG=INTGER
      AVGATM=0.0
      AVGPR=0.0
      DO 926 L=LL,LLL
      AVGATM=AVGATM+PTPL(L)/14.69 /AVG
  926 AVGPR=AVGPR+PR(L)/AVG
      LLL=LLL-1
      COMPAR =PR(LL)
      DO 931 L=LL,LLL
      IF  (COMPAR -PR(L+1)) 930,931,931
  930 COMPAR =PR(L+1)
  931 CONTINUE
      DEVPI  =100.*(COMPAR -AVGPR)/AVGPR
```

```
      CCMPAR =PR(LL)
      DC 934 L=LL,LLL
      IF (CCMPAR -PR(L+1)) 934,934,933
  933 CCMPAR =PR(L+1)
  934 CCNTINUE
      DEVLCW=100.*(AVGPR-CCMPAR )/AVGPR
      WRITE(6,903)  NPTS(K),NPTSS(K),AVGPR,DEVHI   ,DEVLOW,AVGATM
      IF (NPTSS(K+1)+3*(K+1)-43) 936,936,935
  935 IF (NP-2) 944,936,944
  936 K=K+1
  940 CCNTINUE
  944 IF (N-II) 950,950,945
  945 K=K+1
      NP=2
      NX=II+1
      NXX=N
      WRITE(6,904)NP
      GO TO 923
  900 FORMAT(1H1,/ ,9X,7H REPORT,2X,A8,A2,77X,6H SHEET,1X,I1,3H OF,1X,I1
     1,//,33X,53H TURBC PROPULSION LABCRATORY USNPGS, MONTEREY, CALIF. ,
     2///,21X,79H REDUCED PERFORMANCE DATA OF TURBINE FROM TESTS WITH TR
     3ANSONIC TURBINE TEST RIG // ,13H TURBINE TYPE,1X,A8,A3,14H CONFIGU
     4RATION,1X,A5,1X,25H RADIAL ROTOR TIP CLEAR.=,2X,F4.3,32H IN.  AXIA
     5L CLEAR. STATCR-ROTCR=,1X,F5.3,4H IN./ ,24X,13H TEST RUN NO.,1X,I3
     6,3X,13H DATE OF TEST,1X,A8,2X,22H DATA REDUCTION METHOD,1X,A4 // )
  901 FORMAT(7X,105H PCINT  PRESSURE   ISENTROPIC   EFFICIENCY  REFERRED
     1   REFERRED  REFERRED  REFERRED  DEGREE OF  DEGREE OF / ,15X, 96H
     2RATIO      HEAD CCEFF.  TOT-STATIC  FLOW RATE   TORQUE    POWER
     3 SPEED    REACTICN   REACTION / ,24X, 4H (R=,   F5.3,77H IN.)  PER
     4CENT      LBM/SEC     FT-LB       HP         RPM       (HUB)      (TIP)
     5  //)
  902 FORMAT(9X,I2,5X,F6.4,5X,F6.4,8X,F5.2,6X,F6.4,5X,F6.3,4X,F6.3,4X,
     1I5,5X,F5.4,6X,F5.4 )
  903 FCRMAT(/5X,12H FCR PCINTS , I2,3H TO,1X,I2,21H AVG. PRESSURE RATIO
     1=,1X,F6.4,18H , MAX.DEVIATION +,   F5.3,7H PCT. -,   F5.3,19H PCT.
     2, PAVG./PATMC=,1X,F6.4 /)
  904 FCRMAT(/45X,16H CONTD. ON SHEET,1X,I1,/)
  905 FCRMAT(A8)
  906 FCRMAT(A8,A2,10X,A8,A3,9X,A5,5X,A4)
  907 FCRMAT(F5.3)
  908 FCRMAT(I1)
  909 FCRMAT(8(2I5))
  950 CCNTINUE
      RETURN
      END
```

APPENDIX III

REDUCED PERFORMANCE DATA

A. Order of listings

The referred performance parameters and general flow results for runs 58 through 63, 68, 77, and 78 are listed in numerical order. The data point number is listed on the far left hand side of each even numbered page. Read horizontally across both the odd and even numbered pages for the results pertaining to that data point.

B. Definition of parameters

The listed parameters are defined in Sec. 4.

C. Units

1. The units of referred parameters are listed at the top of each column.

2. All velocities are feet per second.

3. All temperatures are degrees Rankine.

4. All angles are degrees. Positive angles are measured in the direction of the rotor rotation vector.

5. All other parameters are dimensionless.

REPORT

TURBC PROPULSION LABORATORY

RECUCED PERFCRMANCE DATA OF TURBINE FR

TURBINE TYPE MOD II CONFIGURATION RADIAL ROTOR

TEST RUN NO. 58 DATE OF TEST

PCINT	PRESSURE RATIO	ISENTRCPIC HEAD COEFF. (R=4.125 IN.)	EFFICIENCY TOT-STATIC PERCENT	REFERRED FLOW RATE LBM/SEC
1	1.3072	3.5161	75.89	3.1706
2	1.3027	3.3283	76.48	3.1434
3	1.3034	3.0016	77.45	3.1430
4	1.3043	2.7702	76.69	3.1403
5	1.3055	2.5500	77.20	3.1407
6	1.3070	2.3756	76.04	3.1351
7	1.3078	2.1948	74.71	3.1330
8	1.3095	2.0608	73.87	3.1412
9	1.2944	1.8055	69.62	3.0882
10	1.2896	1.5040	62.63	3.0785

FCR PCINTS 1 TO 1C AVG. PRESSURE RATIO= 1.3031 , MAX.

PCINT	PRESSURE RATIO	ISENTRCPIC HEAD COEFF. (R=4.125 IN.)	EFFICIENCY TOT-STATIC PERCENT	REFERRED FLOW RATE LBM/SEC
11	1.5044	3.4080	77.31	3.5716
12	1.5044	3.3427	77.18	3.5764
13	1.5055	3.2172	76.50	3.5682
14	1.5065	3.0900	75.21	3.5687
15	1.5063	2.8704	75.93	3.5652
16	1.5055	2.6979	75.74	3.5646
17	1.5049	2.4349	73.65	3.5399

FCR PCINTS 11 TO 17 AVG. PRESSURE RATIO= 1.5054 , MAX.

PCINT	PRESSURE RATIO	ISENTRCPIC HEAD COEFF. (R=4.125 IN.)	EFFICIENCY TOT-STATIC PERCENT	REFERRED FLOW RATE LBM/SEC
18	1.6052	3.6724	74.00	3.6924
19	1.6030	3.5979	74.59	3.6926
20	1.6012	3.4602	75.10	3.6931
21	1.6039	3.3716	74.71	3.6946
22	1.6086	3.1439	74.71	3.6940
23	1.6122	2.7906	74.40	3.6924
24	1.6160	2.4818	73.44	3.6903

FCR PCINTS 18 TO 24 AVG. PRESSURE RATIO= 1.6072 , MAX.

/ USNPGS, MONTEREY, CALIF.

)M TESTS WITH TRANSONIC TURBINE TEST RIG

ΓIP CLEAR.= .033 IN. AXIAL CLEAR. STATOR-ROTOR= 0.620 IN.
/67 DATA REDUCTION METHOD MF

REFERRED TORQUE FT-LB	REFERRED POWER HP	REFERRED SPEED RPM	DEGREE OF REACTION (HUB)	DEGREE OF REACTION (TIP)
15.971	31.253	10279	.0237	.4368
15.429	30.841	10500	.0253	.4406
14.850	31.286	11067	.0295	.4434
14.131	31.029	11534	.0378	.4476
13.673	31.343	12041	.0418	.4537
13.004	30.949	12502	.0485	.4554
12.284	30.449	13021	.0512	.4608
11.828	30.326	13468	.0537	.4637
10.044	26.939	14090	.0572	.4626
8.162	23.817	15328	.0554	.4698
)EVIATION +0.485 PCT.	-1.042 PCT.,	PAVG./PATMO= 1.1202		
22.061	53.610	12765	.0592	.4649
21.839	53.585	12889	.0620	.4674
21.204	53.075	13149	.0619	.4681
20.449	52.270	13427	.0665	.4732
19.877	52.709	13929	.0703	.4736
19.206	52.496	14358	.0704	.4731
17.611	50.646	15107	.0808	.4896
)EVIATION +0.077 PCT.	-0.061 PCT.,	PAVG./PATMO= 1.2005		
24.280	60.906	13177	.0814	.4738
24.193	61.229	13294	.0807	.4724
23.867	61.526	13541	.0825	.4730
23.484	61.430	13741	.0859	.4772
22.742	61.785	14271	.0898	.4829
21.374	61.767	15181	.0921	.4831
19.930	61.214	16135	.0995	.4901
)EVIATION +0.551 PCT.	-0.371 PCT.,	PAVG./PATMO= 1.1513		

GENERAL RESULTS

VELOCITIES (FT/SEC)
RUN NUMBER 58

POINT	V1	V2	W1
1	605.07178	207.99356	274.85962
2	597.00757	206.63495	263.41431
3	594.45630	213.78116	248.46103
4	590.08716	221.61148	235.55698
5	591.10303	230.29192	227.08884
6	589.47021	241.15169	218.47209
7	586.74146	253.98065	210.89293
8	588.83789	266.12573	207.68874
9	578.55103	293.29321	197.85625
10	571.57397	334.58228	199.77663
11	715.95605	249.75797	312.08862
12	712.08521	250.45009	307.12769
13	718.00195	257.80981	304.59253
14	714.79736	264.69409	296.55762
15	710.26782	268.49658	284.04736
16	706.57568	275.07617	274.47314
17	706.21655	296.47681	260.72949
18	765.91309	273.50366	343.10474
19	763.80908	272.98828	338.76196
20	761.28882	274.33911	331.43799
21	759.60278	277.13770	325.72461
22	760.82422	284.98755	315.00879
23	754.14282	297.02563	294.83325
24	755.29541	317.32715	280.41138

TEMPERATURES (DEG R)

POINT	PLENUM TOTAL	STATOR DISCHARGE	ROTOR DISCHARGE
1	562.09106	531.62622	527.00464
2	561.57739	531.91919	526.71216
3	561.57739	532.17212	526.00684
4	561.91992	532.94531	526.28003
5	562.09106	533.01660	525.80078
6	562.09106	533.17700	525.71851
7	562.09106	533.44409	525.67896
8	562.43335	533.58130	525.68262
9	562.26221	534.40942	527.23145
10	561.91992	534.73486	527.89893
11	569.43164	526.77783	515.66895
12	569.43164	527.23779	515.72754
13	569.26123	526.36328	515.61060
14	569.09106	526.57520	515.89136
15	569.09106	527.11230	515.27881
16	569.43164	527.88818	515.47852
17	569.60181	528.10059	515.97534
18	576.73193	527.91797	516.44482
19	577.23975	528.69360	516.64453
20	577.57812	529.35181	516.63306
21	577.91650	529.90356	516.91895
22	577.91650	529.74902	516.22729
23	577.91650	530.59131	515.63672
24	578.08569	530.61572	515.21216

W2	U1	U2
360.56836	385.25928	383.85791
361.71460	393.35669	391.92603
366.84717	414.59009	413.08228
366.37329	432.22485	430.65259
369.87207	451.29883	449.65747
368.46582	468.57349	466.86914
368.86914	488.00732	486.23242
369.05908	504.92212	503.08545
351.25684	528.13477	526.21387
345.92773	574.38037	572.29126
478.76514	481.52930	479.77783
480.55518	486.20801	484.43945
469.26587	495.92480	494.12109
463.11548	506.36157	504.51978
469.98804	525.29150	523.38110
471.52783	541.63037	539.66064
459.71191	569.95361	567.88086
503.76587	500.24341	498.42407
507.64697	504.92212	503.08545
510.66284	514.45898	512.58789
510.05591	522.19653	520.29736
509.50146	542.35010	540.37793
514.02881	576.89966	574.80127
510.89331	613.24829	611.01782

ISENTROPIC FROM T1	TOTAL DISCHARGE
521.87671	530.60449
522.18237	530.26514
522.27148	529.80981
522.75513	530.36670
522.58130	530.21387
522.52222	530.55762
522.59497	531.04663
522.56348	531.57593
523.81592	534.38940
524.18481	537.21411
509.82129	520.85962
510.10327	520.94702
509.20972	521.14136
509.08301	521.72144
509.48730	521.27759
510.27808	521.77490
509.66650	523.28955
507.00830	522.66943
507.89722	522.84570
508.49731	522.89575
508.67773	523.31006
508.04321	522.98560
508.66626	522.97803
508.05859	523.59131

FLOW ANGLES (DEGREES FROM AXIAL)

RUN NUMBER 58

POINT	ALPHA 1	ALPHA 2	BETA 1
1	70.32079	22.30272	42.15587
2	70.14719	23.84007	39.67426
3	70.11757	27.57643	35.54257
4	70.06451	31.71561	31.33595
5	70.04758	34.87515	27.34827
6	70.06096	38.55869	23.05640
7	69.94408	41.87430	17.42496
8	69.93474	44.50960	13.41230
9	70.06828	50.89944	4.56895
10	69.92227	56.62328	-10.83141
11	69.79179	15.32744	37.58510
12	69.62885	15.89893	36.18852
13	69.88020	20.78490	35.82030
14	69.80528	24.35106	33.68849
15	69.67345	26.43724	29.70300
16	69.57333	29.13777	26.04521
17	69.82103	36.23778	20.87721
18	69.79808	14.75771	39.56721
19	69.73656	14.74558	38.65807
20	69.64214	15.93845	36.95975
21	69.60426	17.63284	35.63754
22	69.65169	21.65027	32.87640
23	69.42334	26.88229	25.97505
24	69.53738	33.32198	19.67027

EFFICIENCIES AND LOSSES

POINT	EFFICIENCY TOTAL STATIC	ZETA ROTOR
1	0.75889	0.32537
2	0.76479	0.29808
3	0.77450	0.25530
4	0.76689	0.24568
5	0.77204	0.22698
6	0.76045	0.22761
7	0.74707	0.22185
8	0.73873	0.22409
9	0.69617	0.25877
10	0.62630	0.28213
11	0.77315	0.23893
12	0.77175	0.23084
13	0.76496	0.26331
14	0.75205	0.28067
15	0.75934	0.24480
16	0.75737	0.22521
17	0.73649	0.27003
18	0.73996	0.31226
19	0.74589	0.29334
20	0.75105	0.27657
21	0.74707	0.27970
22	0.74715	0.27907
23	0.74404	0.24596
24	0.73441	0.25364

BETA 2	DELTA BETA	ABSOLUTE MACH 1	RELATIVE MACH 1
-57.74443	99.90030		
-58.49832	98.17258	0.5352	0.2431
-58.89896	94.44153	0.5279	0.2329
-59.03250	90.36845	0.5255	0.2197
-59.28270	86.63097	0.5213	0.2081
-59.21751	82.27391	0.5221	0.2006
-59.15654	76.58150	0.5206	0.1930
-59.05365	72.46594	0.5181	0.1862
-58.22336	62.79230	0.5199	0.1834
-57.85263	47.02121	0.5104	0.1745
-59.79359	97.37869	0.5041	0.1762
-59.91846	96.10698	0.6362	0.2773
-59.09369	94.91399	0.6325	0.2728
-58.62050	92.30899	0.6382	0.2708
-59.23347	88.93648	0.6353	0.2636
-59.36630	85.41151	0.6309	0.2523
-58.65613	79.53334	0.6272	0.2436
-58.33118	97.89839	0.6267	0.2314
-58.66498	97.32304	0.6798	0.3045
-58.89758	95.85733	0.6775	0.3005
-58.81387	94.45142	0.6748	0.2938
-58.67542	91.55182	0.6730	0.2886
-58.97610	84.95116	0.6741	0.2791
-58.73427	78.40454	0.6677	0.2610
		0.6687	0.2483

ZETA STATOR	BLOCKAGE FACTOR
0.04092	0.91621
0.05046	0.91344
0.05598	0.91420
0.06512	0.91524
0.05877	0.91655
0.06277	0.91532
0.06835	0.91578
0.06303	0.91792
0.05507	0.91660
0.06038	0.91971
0.07222	0.92134
0.07888	0.92353
0.06434	0.92108
0.06758	0.92255
0.07655	0.92245
0.08583	0.92254
0.06855	0.92141
0.06647	0.92350
0.07133	0.92381
0.07447	0.92484
0.07719	0.92569
0.07318	0.92581
0.09183	0.92479
0.08412	0.92558

REPORT

TURBC PROPULSION LABCRATOR

REDUCED PERFORMANCE DATA OF TURBINE FR

TURBINE TYPE MOD II CONFIGURATION RADIAL ROTOR
TEST RUN NO. 59 DATE OF TEST

POINT	PRESSURE RATIO	ISENTROPIC HEAD COEFF. (R=4.125 IN.)	EFFICIENCY TOT-STATIC PERCENT	REFERRED FLOW RATE LBM/SEC
1	1.3102	3.4989	75.55	3.1465
2	1.3114	3.3637	76.29	3.1586
3	1.3105	3.0912	77.21	3.1546
4	1.3158	2.9257	75.29	3.1394
5	1.3050	2.4918	76.32	3.1426
6	1.3097	2.4035	74.88	3.1334
7	1.3084	2.2278	73.82	3.1385
8	1.3100	2.0497	72.16	3.1347
9	1.3115	1.7962	69.23	3.1301
10	1.2895	1.5472	66.13	3.1021

FCR PCINTS 1 TO 10 AVG. PRESSURE RATIO= 1.3082 , MAX.

POINT	PRESSURE RATIO	ISENTROPIC HEAD COEFF. (R=4.125 IN.)	EFFICIENCY TOT-STATIC PERCENT	REFERRED FLOW RATE LBM/SEC
11	1.5083	3.2610	76.87	3.5734
12	1.5104	3.1555	77.23	3.5757
13	1.5123	3.0453	76.61	3.5724
14	1.5123	2.9609	76.56	3.5725
15	1.5159	2.7908	76.62	3.5724
16	1.5173	2.4563	75.90	3.5727

FCR PCINTS 11 TO 16 AVG. PRESSURE RATIO= 1.5127 , MAX.

POINT	PRESSURE RATIO	ISENTROPIC HEAD COEFF. (R=4.125 IN.)	EFFICIENCY TOT-STATIC PERCENT	REFERRED FLOW RATE LBM/SEC
17	1.4034	3.4304	77.48	3.3434
18	1.4034	3.3090	76.73	3.3337
19	1.4038	3.1759	74.95	3.3405
20	1.4025	3.0413	76.57	3.3448
21	1.4025	2.9174	78.40	3.3407
22	1.4029	2.8387	78.19	3.3385
23	1.4055	2.6015	77.95	3.3408
24	1.4089	2.3109	76.30	3.3337
25	1.4099	2.0247	74.04	3.3259

FCR PCINTS 17 TO 25 AVG. PRESSURE RATIO= 1.4047 , MAX.

CONTD. ON SHEE

Y USNPGS, MONTEREY, CALIF.

OM TESTS WITH TRANSONIC TURBINE TEST RIG

TIP CLEAR.= .033 IN. AXIAL CLEAR. STATOR-ROTOR= 1.000 IN.
/67 DATA REDUCTION METHOD MF

REFERRED TORQUE FT-LB	REFERRED POWER HP	REFERRED SPEED RPM	DEGREE OF REACTION (HUB)	DEGREE OF REACTION (TIP)
15.806	31.133	10347	.0083	.4470
15.732	31.655	10570	.0110	.4530
15.228	31.925	11013	.0123	.4479
14.477	31.418	11400	.0190	.4450
13.361	30.963	12174	.0278	.4564
12.920	30.684	12475	.0358	.4531
12.261	30.193	12936	.0386	.4680
11.507	29.604	13515	.0412	.4696
10.341	28.479	14467	.0410	.4725
8.809	25.341	15112	.0101	.4565

DEVIATION +0.578 PCT. -1.428 PCT., PAVG./PATMO= 1.1268

21.530	53.643	13088	.0474	.4746
21.325	54.099	13326	.0510	.4766
20.793	53.771	13584	.0527	.4773
20.490	53.737	13777	.0545	.4798
19.960	54.065	14229	.0580	.4803
18.571	53.678	15183	.0625	.4858

DEVIATION +0.303 PCT. -0.292 PCT., PAVG./PATMO= 1.2082

19.006	42.137	11646	.0236	.4592
18.432	41.609	11858	.0259	.4622
17.682	40.759	12109	.0281	.4648
17.677	41.586	12358	.0315	.4626
17.706	42.529	12618	.0326	.4666
17.414	42.422	12797	.0348	.4652
16.674	42.539	13402	.0380	.4698
15.403	41.836	14268	.0488	.4768
13.971	40.577	15257	.0519	.4781

DEVIATION +0.366 PCT. -0.160 PCT., PAVG./PATMO= 1.1645

T 2

REPORT

TURBO PROPULSION LABORATORY

REDUCED PERFORMANCE DATA OF TURBINE FRO

TURBINE TYPE MOD II CONFIGURATION RADIAL ROTOR T

TEST RUN NO. 59 DATE OF TEST

POINT	PRESSURE RATIO	ISENTROPIC HEAD COEFF. (R=4.125 IN.)	EFFICIENCY TOT-STATIC PERCENT	REFERRED FLOW RATE LBM/SEC
26	1.5991	3.6349	75.63	3.6862
27	1.5990	3.5212	75.45	3.6847
28	1.6009	3.4181	75.32	3.6821
29	1.6008	3.1825	76.14	3.6799
30	1.6006	2.9863	75.76	3.6786
31	1.6030	2.7969	76.32	3.6777
32	1.6073	2.4624	75.85	3.6737

FOR POINTS 26 TO 32 AVG. PRESSURE RATIO= 1.6015 , MAX.D

USNPGS, MONTEREY, CALIF.

M TESTS WITH TRANSONIC TURBINE TEST RIG

IP CLEAR.= .033 IN. AXIAL CLEAR. STATOR-ROTOR= 1.000 IN.
/67 DATA REDUCTION METHOD MF

REFERRED TORQUE FT-LB	REFERRED POWER HP	REFERRED SPEED RPM	DEGREE OF REACTION (HUB)	DEGREE OF REACTION (TIP)
24.555	61.676	13195	.0647	.4821
24.099	61.498	13405	.0664	.4833
23.715	61.500	13622	.0681	.4855
23.116	62.122	14117	.0725	.4890
22.271	61.774	14571	.0752	.4898
21.738	62.396	15078	.0759	.4901
20.304	62.278	16113	.0835	.4979

)EVIATION +0.362 PCT. -0.159 PCT., PAVG./PATMO= 1.1520

GENERAL RESULTS

VELOCITIES (FT/SEC)
RUN NUMBER 59

POINT	V1	V2	W1
1	613.06104	210.39188	278.26196
2	605.26318	208.97163	267.47046
3	608.49756	217.17159	259.16675
4	611.15332	228.75798	251.28174
5	596.76416	240.12752	227.86395
6	595.41309	247.21349	221.74252
7	594.74268	259.96875	214.60435
8	591.09570	273.66455	207.32816
9	593.74536	303.43140	202.04755
10	588.38184	333.72192	199.78871
11	727.23682	258.57690	311.47119
12	725.38477	260.72949	304.78857
13	725.27759	265.66235	299.55103
14	723.05737	268.16284	293.91187
15	720.25830	273.90576	284.04028
16	718.12671	291.87915	267.82593
17	684.85083	231.91692	304.70898
18	683.10498	237.35011	297.93628
19	680.62866	247.40923	290.30957
20	680.32251	246.60745	284.42310
21	679.27588	245.31918	277.42456
22	672.09619	245.70757	269.16724
23	672.05908	257.58789	257.19287
24	673.43921	280.70361	243.37457
25	671.08252	306.87842	229.64301
26	774.23022	272.51514	346.51904
27	773.37524	274.91089	340.76929
28	773.14575	277.80908	335.36328
29	769.99902	281.60107	321.81445
30	767.21997	289.07642	310.76001
31	762.31128	292.89771	298.78857
32	757.48120	308.90332	280.37109

W2	U1	U2
355.39307	388.67822	387.26465
366.95581	397.27954	395.83447
365.44995	413.94238	412.43677
356.57007	428.55396	426.99512
364.26343	457.77686	456.11182
364.13574	469.11328	467.40723
360.51074	486.42383	484.65454
362.71460	508.19678	506.34863
360.30005	544.00586	542.02734
344.28125	568.33423	566.26709
471.41040	495.92480	494.12109
476.26050	505.10205	503.26489
473.08350	515.10669	513.23340
474.43213	522.62842	520.72778
479.42993	539.68701	537.72412
479.64697	576.14380	574.04834
412.10889	440.89795	439.29443
406.90234	448.77954	447.14746
397.55688	458.13672	456.47021
404.56885	467.56567	465.86523
414.86353	477.39063	475.65430
420.12720	484.15649	482.39575
420.84668	507.04541	505.20117
416.33301	539.83105	537.86768
414.04370	577.25928	575.16016
511.57397	504.56201	502.72705
509.17114	512.83936	510.97412
508.30249	521.29688	519.40088
513.65308	540.37109	538.40552
511.75488	557.82544	555.79688
520.67041	577.25928	575.16016
526.03687	616.95508	614.71118

TEMPERATURES (DEG R)

POINT	PLENUM TOTAL	STATOR DISCHARGE	ROTOR DISCHARGE
1	564.65625	533.38159	529.22339
2	565.33936	534.85522	529.50781
3	565.33936	534.52856	528.90088
4	565.51025	534.42993	528.99341
5	565.85156	536.21753	529.37012
6	565.85156	536.35156	529.27661
7	565.85156	536.41797	529.29224
8	565.85156	536.77783	529.25098
9	565.85156	536.51660	528.93237
10	566.02246	537.21509	530.47827
11	574.52905	530.52051	519.95264
12	574.86816	531.08350	519.78491
13	575.37671	531.60498	520.28784
14	575.88501	532.38086	520.67407
15	575.71558	532.54761	519.95850
16	576.22388	533.31104	519.93530
17	573.51099	534.48291	527.95923
18	573.17163	534.34229	527.82959
19	572.83203	534.28369	528.01807
20	572.83203	534.31836	527.29785
21	572.83203	534.43677	526.38159
22	572.83203	535.24414	526.44385
23	572.83203	535.24829	525.85937
24	572.83203	535.09375	525.42285
25	572.83203	535.35742	525.27905
26	585.17017	535.29028	523.35083
27	585.67456	535.90479	523.83545
28	586.01099	536.27075	523.96558
29	586.34717	537.01099	523.49780
30	586.51514	537.53442	523.58960
31	586.51514	538.15918	522.82788
32	586.68311	538.93799	522.22314

ISENTROPIC FROM T1	TOTAL DISCHARGE
523.59912	532.90674
524.82764	533.14160
524.61450	532.82544
524.29785	533.34790
525.94946	534.16821
525.85205	534.36206
525.57983	534.91602
525.79687	535.48291
525.43286	536.59375
527.73608	539.74561
513.35522	525.51636
513.66846	525.44165
514.04321	526.16064
514.65723	526.65796
514.59302	526.20142
514.96924	527.02441
521.35107	532.43481
521.07642	532.51733
520.88232	533.11157
520.93140	532.35840
520.90991	531.38940
521.66943	531.46753
521.39478	531.38062
520.67725	531.97949
520.79248	533.11548
514.50708	529.53052
514.99658	530.12427
515.15259	530.38770
515.58521	530.09644
515.97827	530.54321
516.47070	529.96655
516.52979	530.16333

FLOW ANGLES (DEGREES FROM AXIAL)

RUN NUMBER 59

POINT	ALPHA 1	ALPHA 2	BETA 1
1	70.59125	24.63844	42.93517
2	70.25215	23.39796	40.12894
3	70.35716	27.85992	37.88387
4	70.58066	33.39029	36.03708
5	70.10620	37.38863	26.97951
6	70.14183	39.49748	24.19919
7	70.16603	43.20201	19.89769
8	70.03320	46.10776	13.20712
9	70.15860	51.11537	4.11323
10	70.20630	56.04420	-4.22384
11	69.99789	20.33228	36.99933
12	69.95900	21.08983	35.35403
13	69.88861	23.83044	33.64110
14	69.86005	24.98961	32.10754
15	69.74545	27.12794	28.61507
16	69.66498	33.43983	21.28596
17	70.87402	22.18254	42.57426
18	70.87019	25.29848	41.29103
19	70.77545	29.58777	39.46866
20	70.73326	29.79395	37.88393
21	70.76463	29.33020	36.22942
22	70.55257	29.45518	33.76372
23	70.54350	33.71577	29.49689
24	70.57672	40.16486	23.04788
25	70.61256	45.91084	14.05512
26	69.94922	13.78541	40.00073
27	69.91418	15.99491	38.79381
28	69.91113	17.87578	37.64122
29	69.86955	20.32784	34.56747
30	69.78464	23.97716	31.44864
31	69.63132	25.58481	27.37498
32	69.55777	31.17242	19.33398

BETA 2	DELTA BETA	ABSOLUTE MACH 1	RELATIVE MACH 1
-57.44554	100.38071	0.5414	0.2457
-58.49013	98.61906	0.5337	0.2359
-58.30620	96.19006	0.5368	0.2286
-57.61150	93.64857	0.5391	0.2217
-58.41461	85.39412	0.5256	0.2007
-58.40718	82.60637	0.5243	0.1953
-58.28790	78.18559	0.5237	0.1890
-58.46017	71.66728	0.5203	0.1825
-58.08430	62.19753	0.5228	0.1779
-57.21953	52.99568	0.5177	0.1758
-59.04654	96.04587	0.6439	0.2758
-59.28407	94.63811	0.6419	0.2697
-59.09074	92.73184	0.6415	0.2650
-59.18184	91.28938	0.6391	0.2598
-59.43832	88.05339	0.6365	0.2510
-59.48280	80.76877	0.6342	0.2365
-58.59361	101.16788	0.6041	0.2688
-58.17223	99.46326	0.6027	0.2629
-57.23647	96.70512	0.6005	0.2561
-58.06316	95.94708	0.6002	0.2509
-58.96747	95.19688	0.5992	0.2447
-59.38641	93.15013	0.5925	0.2373
-59.39467	88.89156	0.5924	0.2267
-58.98650	82.03438	0.5937	0.2146
-58.95627	73.01138	0.5915	0.2024
-58.84502	98.84575	0.6825	0.3054
-58.73372	97.52753	0.6813	0.3002
-58.65710	96.29832	0.6809	0.2953
-59.06348	93.63095	0.6776	0.2832
-58.92709	90.37573	0.6749	0.2734
-59.51045	86.88544	0.6702	0.2627
-59.83841	79.17239	0.6654	0.2463

EFFICIENCIES AND LOSSES

POINT	EFFICIENCY TOTAL STATIC	ZETA ROTOR
1	0.75552	0.35226
2	0.76286	0.29884
3	0.77211	0.28316
4	0.75288	0.31239
5	0.76317	0.24316
6	0.74884	0.24382
7	0.73818	0.26281
8	0.72161	0.24800
9	0.69230	0.25403
10	0.66134	0.22948
11	0.76867	0.26730
12	0.77225	0.24938
13	0.76612	0.25591
14	0.76561	0.24816
15	0.76619	0.22464
16	0.75898	0.21253
17	0.77480	0.32245
18	0.76729	0.33289
19	0.74951	0.35576
20	0.76569	0.32302
21	0.78402	0.28144
22	0.78192	0.25077
23	0.77955	0.23866
24	0.76303	0.25442
25	0.74043	0.24735
26	0.75627	0.29237
27	0.75449	0.29433
28	0.75323	0.29456
29	0.76138	0.26924
30	0.75765	0.26357
31	0.76318	0.22525
32	0.75849	0.20461

ZETA STATOR	BLOCKAGE FACTOR
0.03051	0.90579
0.05363	0.91012
0.04382	0.90884
0.04709	0.90074
0.05258	0.91519
0.06623	0.90930
0.05368	0.91582
0.06654	0.91428
0.06028	0.91221
0.04862	0.91401
0.05731	0.92014
0.06208	0.92089
0.06427	0.91974
0.06802	0.92054
0.07744	0.91982
0.07928	0.92113
0.02198	0.90150
0.02294	0.89990
0.02707	0.90240
0.02488	0.90448
0.02442	0.90436
0.04531	0.90367
0.04528	0.90432
0.03635	0.90390
0.04206	0.90208
0.05718	0.92261
0.05806	0.92272
0.05885	0.92214
0.06176	0.92292
0.06631	0.92322
0.08030	0.92247
0.08704	0.92279

REPORT

TURBO PROPULSION LABORATOR

REDUCED PERFORMANCE DATA OF TURBINE FR

TURBINE TYPE MOD II CONFIGURATION RADIAL ROTOR
TEST RUN NO. 60 DATE OF TEST

POINT	PRESSURE RATIO	ISENTROPIC HEAD COEFF. (R=4.125 IN.)	EFFICIENCY TOT-STATIC PERCENT	REFERRED FLOW RATE LBM/SEC
1	1.2981	3.4730	75.31	3.1518
2	1.3023	2.7825	75.53	3.1465
3	1.3043	2.5620	75.22	3.1424
4	1.3047	2.3895	74.95	3.1387
5	1.2977	2.1750	72.92	3.1407
6	1.2985	1.9949	72.36	3.1255
7	1.2996	1.7736	67.76	3.1294
8	1.2987	1.5296	61.82	3.1360

FOR POINTS 1 TO 8 AVG. PRESSURE RATIO= 1.3005 , MAX.

9	1.4003	3.5092	75.21	3.4135
10	1.4022	3.0094	76.05	3.4085
11	1.4036	2.8271	75.42	3.4059
12	1.3962	2.6015	75.34	3.3853
13	1.3996	2.4033	74.84	3.3812
14	1.3962	2.2430	73.42	3.3585
15	1.3964	1.9770	70.51	3.3565
16	1.3996	1.7483	68.37	3.3642

FOR POINTS 9 TO 16 AVG. PRESSURE RATIO= 1.3993 , MAX.

17	1.4992	3.5028	74.14	3.5784
18	1.4998	3.3294	74.71	3.5790
19	1.4955	3.1597	74.51	3.5639
20	1.4950	2.8544	75.94	3.5572
21	1.4969	2.7163	75.63	3.5498
22	1.4971	2.5249	74.79	3.5548
23	1.4940	2.3671	74.28	3.5420
24	1.4953	2.1156	71.09	3.5395

FOR POINTS 17 TO 24 AVG. PRESSURE RATIO= 1.4966 , MAX.

CONTD. ON SHEE

Y USNPGS, MONTEREY, CALIF.

OM TESTS WITH TRANSONIC TURBINE TEST RIG

TIP CLEAR.= .033 IN. AXIAL CLEAR. STATOR-ROTOR= 0.200 IN.
/67 DATA REDUCTION METHOD MF

REFERRED TORQUE FT-LB	REFERRED POWER HP	REFERRED SPEED RPM	DEGREE OF REACTION (HUB)	DEGREE OF REACTION (TIP)
15.460	30.055	10212	.0535	.4014
13.937	30.450	11477	.0625	.4157
13.391	30.458	11948	.0676	.4210
12.828	30.346	12427	.0702	.4269
11.798	28.967	12897	.0717	.4281
11.171	28.669	13482	.0729	.4336
9.891	26.966	14321	.0713	.4360
8.388	24.593	15402	.0673	.4435

DEVIATION +0.324 PCT. -0.215 PCT., PAVG./PATMO= 1.1297

18.992	41.504	11480	.0715	.4144
17.793	42.066	12419	.0756	.4237
17.114	41.804	12832	.0765	.4283
16.178	40.890	13277	.0810	.4347
15.480	40.849	13862	.0849	.4382
14.523	39.532	14299	.0854	.4378
13.089	37.959	15234	.0853	.4476
12.002	37.133	16252	.0827	.4493

DEVIATION +0.309 PCT. -0.220 PCT., PAVG./PATMO= 1.1695

21.400	51.086	12540	.0896	.4300
21.039	51.542	12869	.0933	.4323
20.286	50.840	13165	.0940	.4354
19.608	51.686	13847	.0940	.4388
19.037	51.515	14215	.0956	.4409
18.179	51.033	14746	.0964	.4420
17.377	50.258	15193	.0959	.4485
15.726	48.157	16086	.0957	.3657

DEVIATION +0.215 PCT. -0.173 PCT., PAVG./PATMO= 1.2014

T 2

REPORT

TURBC PROPULSION LABCRATORY

RECUCED PERFCRMANCE DATA OF TURBINE FRC

TURBINE TYPE MOD II CONFIGURATION RADIAL ROTOR 1

TEST RUN NO. 60 DATE OF TEST

POINT	PRESSURE RATIO	ISENTROPIC HEAD COEFF. (R=4.125 IN.)	EFFICIENCY TOT-STATIC PERCENT	REFERRED FLOW RATE LBM/SEC
25	1.6052	3.6541	74.12	3.7094
26	1.6076	3.4064	74.64	3.7051
27	1.6065	3.1705	74.67	3.7033
28	1.6106	2.9974	75.01	3.6875
29	1.6000	2.7898	74.61	3.6813
30	1.6151	2.6142	75.74	3.6796
31	1.6155	2.4948	74.99	3.6940
32	1.5974	2.3780	75.04	3.6621

FOR POINTS 25 TO 32 AVG. PRESSURE RATIO= 1.6073 , MAX.D

' USNPGS, MONTEREY, CALIF.

)M TESTS WITH TRANSONIC TURBINE TEST RIG

:IP CLEAR.= .033 IN. AXIAL CLEAR. STATOR-ROTOR= 0.200 IN.
/67 DATA REDUCTION METHOD MF

REFERRED TORQUE FT-LB	REFERRED POWER HP	REFERRED SPEED RPM	DEGREE OF REACTION (HUB)	DEGREE OF REACTION (TIP)
24.374	61.296	13210	.1115	.4435
23.704	61.830	13702	.1146	.4485
22.851	61.741	14193	.1138	.4500
22.281	62.071	14634	.1131	.4520
21.208	60.841	15070	.1147	.4538
21.022	62.876	15712	.1181	.4597
20.418	62.531	16088	.1189	.4639
19.556	60.666	16296	.1150	.4603

)EVIATION +0.516 PCT. −0.614 PCT., PAVG./PATMO= 1.1690

GENERAL RESULTS

VELOCITIES (FT/SEC)
RUN NUMBER 60

POINT	V1	V2	W1
1	596.91650	207.49220	269.58472
2	593.15698	227.07161	238.55130
3	593.52026	237.42427	229.95544
4	595.87866	249.26410	222.59268
5	581.65894	260.37476	210.26653
6	580.48755	271.88452	204.50180
7	580.33838	302.31274	200.89865
8	580.59863	341.41821	204.72096
9	668.45410	233.54947	300.68530
10	662.48242	244.12029	275.21973
11	662.73047	253.78996	266.70532
12	654.26270	260.34668	252.69954
13	657.63525	274.09839	244.89256
14	652.69800	285.45557	236.38019
15	650.56836	313.33545	226.69427
16	651.40869	338.66138	224.91476
17	719.45312	257.60498	319.29370
18	717.99194	259.94067	310.74780
19	712.61865	263.91724	299.91528
20	712.35498	270.83569	285.36279
21	709.01733	275.84839	276.71973
22	708.60327	288.65991	268.27734
23	706.68164	298.51831	260.27222
24	707.11938	327.55029	255.29721
25	769.38330	275.31616	344.93213
26	764.68628	278.81567	330.06030
27	762.73267	285.22949	317.93896
28	761.47583	288.78687	307.89014
29	757.23145	297.53394	296.66455
30	762.29980	303.25244	289.29956
31	758.59595	311.32056	283.35669
32	755.41211	316.50781	276.32178

W2	U1	U2
355.85889	383.89185	382.49561
359.52734	431.57666	430.00708
360.98047	449.42725	447.79297
359.28857	467.56567	465.86523
358.90454	485.27197	483.50708
363.05005	507.26123	505.41626
355.45483	538.93164	536.97119
349.93164	579.59863	577.49048
413.19946	433.55615	431.97949
419.62500	469.11328	467.40723
416.21265	484.69653	482.93359
415.61792	501.50317	499.67896
414.55322	523.67212	521.76758
410.47070	540.26294	538.29810
406.40308	575.60400	573.51025
410.93018	614.07568	611.84229
457.21411	475.08716	473.35937
460.56348	487.68359	485.90967
458.29614	498.98389	497.16895
464.70752	524.89575	522.98657
466.65308	538.85937	536.89966
463.53198	559.08521	557.05176
461.09814	576.10767	574.01270
452.07300	609.97314	607.75488
506.19482	503.19458	501.36450
512.47852	522.30469	520.40479
511.42920	541.41455	539.44556
515.82568	558.47314	556.44189
508.85205	575.28027	573.18774
521.98096	599.78833	597.60693
522.66138	614.14795	611.91431
512.84888	622.17334	619.91040

TEMPERATURES (DEG R)

POINT	PLENUM TOTAL	STATOR DISCHARGE	ROTOR DISCHARGE
1	565.51025	535.86108	531.28198
2	565.85156	536.57471	530.44141
3	566.19312	536.88037	530.31543
4	566.53418	536.98804	530.23706
5	566.53418	538.38135	531.19922
6	566.53418	538.49463	530.85132
7	566.70483	538.67969	531.34888
8	566.70483	538.65454	531.74951
9	570.79272	533.61108	526.81372
10	570.96289	534.44263	525.96021
11	570.96289	534.41528	525.77734
12	570.96289	535.34326	526.13086
13	571.13281	535.14502	525.66943
14	571.30298	535.85352	526.30640
15	571.30298	536.08447	526.41699
16	571.30298	535.99341	525.92334
17	574.35938	531.28784	522.23975
18	574.69873	531.80200	522.04272
19	574.86816	532.61108	522.46802
20	575.03760	532.81177	521.45142
21	575.03760	533.20654	521.28223
22	575.20728	533.42505	521.34595
23	575.37671	533.82080	521.56519
24	575.37671	533.76929	521.96191
25	580.62012	531.36279	519.78857
26	581.46387	532.80615	519.85205
27	582.30713	533.89771	520.36719
28	582.81299	534.56299	520.12183
29	583.14990	535.43628	521.01367
30	583.14990	534.79541	518.87012
31	583.14990	535.26416	518.98584
32	583.31836	535.83374	520.06738

ISENTROPIC FROM T1	TOTAL DISCHARGE
526.45923	534.86450
526.56396	534.73193
526.59009	535.00610
526.50684	535.40723
528.03882	536.84058
527.98779	537.00244
528.11523	538.95386
528.04053	541.44922
520.62158	531.35254
521.02905	530.91919
520.81738	531.13696
521.66089	531.77100
521.17578	531.92114
521.96802	533.08691
521.92749	534.58667
521.75806	535.46704
514.58691	527.76172
514.88696	527.66528
515.67676	528.26392
515.77490	527.55518
515.98657	527.61401
516.13599	528.27954
516.41650	528.98047
518.98535	530.88965
510.46143	526.09595
511.48120	526.32080
512.53564	527.13696
512.99976	527.06152
514.03052	528.38013
512.62842	526.52246
512.87427	527.05078
514.23535	528.40332

FLOW ANGLES (DEGREES FROM AXIAL)

RUN NUMBER 60

POINT	ALPHA 1	ALPHA 2	BETA 1
1	70.12555	23.27457	41.17168
2	70.02550	33.29710	31.85452
3	70.01773	36.53429	28.11427
~~4~~	~~70.15735~~	~~40.25459~~	~~24.67752~~
5	69.74147	43.32562	16.69522
6	69.73343	45.95955	10.50621
7	69.75447	51.30089	1.58383
~~8~~	~~69.67366~~	~~56.18065~~	~~-9.88766~~
9	69.91943	20.42540	40.24582
10	69.76682	26.54305	33.64627
11	69.82042	30.49716	30.99736
~~12~~	~~69.75983~~	~~33.79582~~	~~26.40007~~
13	69.88152	37.85228	22.53046
14	69.83392	41.28296	17.84143
15	69.86528	46.78522	8.93418
~~16~~	~~69.80295~~	~~50.58835~~	~~-0.69329~~
17	69.75453	19.49399	38.76472
18	69.69388	21.25023	36.69446
19	69.66797	24.01357	34.35202
~~20~~	~~69.73470~~	~~27.52425~~	~~30.15831~~
21	69.66547	29.66226	27.07990
22	69.61591	33.77127	23.07430
23	69.67595	36.94687	19.42946
~~24~~	~~69.29051~~	~~43.14853~~	~~11.62787~~
25	69.69371	14.88838	39.27826
26	69.58099	17.22316	36.07063
27	69.53946	21.10298	33.00813
~~28~~	~~69.55307~~	~~23.26625~~	~~30.23270~~
29	69.55072	27.62206	26.90227
30	69.61208	29.16492	23.37039
31	69.42662	31.34332	19.81793
~~32~~	~~69.66180~~	~~34.35603~~	~~18.16502~~

BETA 2	DELTA BETA	ABSOLUTE MACH 1	RELATIVE MACH 1
-57.61368	98.78535		
-58.13632	89.99084	0.5259	0.2375
-58.09726	86.21153	0.5222	0.2100
-58.03015	82.70767	0.5224	0.2024
-58.14604	74.84126	0.5244	0.1959
-58.62727	69.13348	0.5112	0.1848
-57.87584	59.45966	0.5102	0.1797
-57.10950	47.22183	0.5099	0.1765
-58.01578	98.26160	0.5102	0.1799
-58.63820	92.28447	0.5901	0.2655
-58.30461	89.30197	0.5844	0.2428
-58.63007	85.03014	0.5847	0.2353
-58.52859	81.05905	0.5767	0.2227
-58.49373	76.33516	0.5798	0.2159
-58.13435	67.06853	0.5750	0.2083
-58.45067	57.75737	0.5730	0.1997
-57.91841	96.68314	0.5738	0.1981
-58.26292	94.95738	0.6366	0.2825
-58.26276	92.61478	0.6350	0.2748
-58.87917	89.03748	0.6297	0.2650
-59.09212	86.17201	0.6294	0.2521
-58.82448	81.89877	0.6262	0.2444
-58.84175	78.27121	0.6257	0.2369
-58.08763	69.71550	0.6238	0.2297
-58.28905	97.56731	0.6242	0.2254
-58.69072	94.76135	0.6807	0.3052
-58.64711	91.65524	0.6756	0.2916
-59.04758	89.28027	0.6732	0.2806
-58.79694	85.69920	0.6717	0.2716
-59.51515	82.88554	0.6674	0.2615
-59.42139	79.23932	0.6723	0.2551
-59.37007	77.53510	0.6687	0.2498
		0.6655	0.2434

EFFICIENCIES AND LOSSES

PCINT	EFFICIENCY TOTAL STATIC	ZETA ROTOR
1	0.75313	0.31793
2	0.75528	0.27059
3	0.75218	0.26190
4	0.74948	0.26448
5	0.72920	0.23555
6	0.72365	0.21585
7	0.67760	0.24487
8	0.61821	0.27742
9	0.75207	0.30741
10	0.76054	0.25685
11	0.75423	0.26141
12	0.75342	0.24332
13	0.74835	0.24575
14	0.73422	0.24359
15	0.70507	0.25442
16	0.68372	0.23819
17	0.74135	0.30929
18	0.74712	0.29256
19	0.74513	0.28427
20	0.75944	0.24538
21	0.75629	0.23191
22	0.74791	0.23193
23	0.74283	0.23217
24	0.71087	0.15843
25	0.74125	0.30778
26	0.74639	0.28087
27	0.74669	0.26899
28	0.75012	0.24823
29	0.74615	0.25003
30	0.75737	0.22172
31	0.74988	0.21808
32	0.75038	0.21702

ZETA STATOR	BLOCKAGE FACTOR
0.05331	0.91726
0.06250	0.91685
0.06073	0.91606
0.04935	0.91654
0.07458	0.92415
0.07606	0.92046
0.07926	0.92074
0.07372	0.92438
0.05891	0.92192
0.07093	0.92214
0.06944	0.92167
0.07258	0.92263
0.06509	0.92094
0.07288	0.91681
0.07298	0.91818
0.07702	0.91821
0.06880	0.92374
0.07031	0.92469
0.07576	0.92325
0.07387	0.92232
0.08281	0.92033
0.08330	0.92187
0.08006	0.92098
0.13269	0.90495
0.06701	0.92708
0.07701	0.92668
0.08135	0.92666
0.08875	0.92179
0.08552	0.92382
0.08394	0.92068
0.08994	0.92501
0.08254	0.92096

REPORT

TURBO PROPULSION LABORATORY

RECUCED PERFCRMANCE DATA OF TURBINE FRC

TURBINE TYPE MOD II CONFIGURATION RADIAL ROTOR 1
TEST RUN NO. 61 DATE OF TEST

POINT	PRESSURE RATIO	ISENTRCPIC HEAC COEFF. (R=4.125 IN.)	EFFICIENCY TOT-STATIC PERCENT	REFERRED FLOW RATE LBM/SEC
1	1.3076	3.4936	75.64	3.1764
2	1.3005	2.7523	75.60	3.1331
3	1.3018	2.5674	75.32	3.1296
4	1.3023	2.3932	75.64	3.1209
5	1.3018	2.1951	74.66	3.1208
6	1.3026	2.0432	72.44	3.1176
7	1.3027	1.7843	67.96	3.1171
8	1.3029	1.5503	62.71	3.1153

FCR PCINTS 1 TO 8 AVG. PRESSURE RATIC= 1.3028 , MAX.C

POINT	PRESSURE RATIO	ISENTRCPIC HEAC COEFF. (R=4.125 IN.)	EFFICIENCY TOT-STATIC PERCENT	REFERRED FLOW RATE LBM/SEC
9	1.4045	3.3912	76.11	3.4068
10	1.3954	2.9578	77.13	3.3683
11	1.3972	2.7664	76.81	3.3687
12	1.3961	2.5927	75.77	3.3647
13	1.3967	2.2261	73.96	3.3586
14	1.3981	2.1180	72.35	3.3545
15	1.3979	1.9703	71.97	3.3524
16	1.3965	1.7394	68.50	3.3582

FCR PCINTS 9 TO 16 AVG. PRESSURE RATIO= 1.3978 , MAX.I

USNPGS, MONTEREY, CALIF.

)M TESTS WITH TRANSONIC TURBINE TEST RIG

'IP CLEAR.= .033 IN. AXIAL CLEAR. STATOR-ROTOR= 0.410 IN.
67 DATA REDUCTION METHOD MF

REFERRED TORQUE FT-LB	REFERRED POWER HP	REFERRED SPEED RPM	DEGREE OF REACTION (HUB)	DEGREE OF REACTION (TIP)
15.904	31.237	10317	.0385	.4321
13.780	30.194	11510	.0505	.4443
13.268	30.156	11939	.0559	.4492
12.839	30.245	12375	.0627	.4520
12.129	29.813	12912	.0628	.4551
11.353	28.956	13398	.0668	.4618
9.954	27.175	14340	.0667	.4625
8.559	25.071	15388	.0625	.4658

)EVIATION +0.369 PCT. -0.174 PCT., PAVG./PATMO= 1.1276

18.936	42.271	11726	.0546	.4477
17.558	41.587	12442	.0623	.4532
16.942	41.567	12888	.0632	.4566
16.141	40.860	13298	.0689	.4605
14.583	39.866	14360	.0755	.4668
13.917	39.059	14743	.0786	.4675
13.342	38.816	15283	.0786	.4706
11.935	36.903	16242	.0765	.4744

)EVIATION +0.478 PCT. -0.169 PCT., PAVG./PATMO= 1.1658

GENERAL RESULTS

VELOCITIES (FT/SEC)
RUN NUMBER 61

POINT	V1	V2	W1
1	608.63745	209.60948	276.56494
2	594.60693	228.85414	238.01244
3	592.09009	237.23883	228.03453
4	591.05347	243.77751	219.53047
5	589.83594	257.54810	211.79671
6	587.65332	272.32666	205.30698
7	588.79810	306.50537	200.38696
8	588.50391	342.22925	201.69652
9	668.70215	233.99501	294.43213
10	661.29663	241.37057	271.46411
11	660.16870	250.11600	262.04297
12	655.65356	258.97949	251.79199
13	655.06934	286.58911	235.35686
14	650.38794	296.45215	229.73326
15	650.93115	307.83301	225.98172
16	651.30957	339.26733	223.57727

TEMPERATURES (DEG R)

POINT	PLENUM TOTAL	STATOR DISCHARGE	ROTOR DISCHARGE
1	566.02246	535.19751	530.73389
2	566.53418	537.11401	531.14844
3	566.70483	537.53320	530.98975
4	567.04590	537.97632	530.87134
5	567.04590	538.09595	530.74243
6	567.04590	538.30981	530.94507
7	567.21655	538.36841	531.29688
8	567.38696	538.56763	531.69263
9	569.60181	532.39258	524.88184
10	570.28247	533.89282	525.42139
11	570.45264	534.18701	525.24561
12	570.62280	534.85156	525.66211
13	570.62280	534.91528	525.29639
14	570.62280	535.42383	525.55127
15	570.79272	535.53491	525.34912
16	570.96289	535.66406	525.72949

W2	U1	U2
359.21362	388.03052	386.61914
356.34058	433.08838	431.51318
359.40112	449.28345	447.64941
363.32153	465.83813	464.14380
362.64697	486.06396	484.29614
358.90039	504.34619	502.51196
350.74219	539.90332	537.93945
347.65210	579.41895	577.31152
418.96265	442.40942	440.80029
417.00854	469.68896	467.98071
417.61035	486.60376	484.83398
414.73120	502.15088	500.32446
410.91699	542.27832	540.30615
411.30078	556.70996	554.68506
413.58911	577.18750	575.08813
408.21899	613.50024	611.26880

ISENTROPIC FROM T1	TOTAL DISCHARGE
525.18018	534.38989
526.78198	535.50659
526.94556	535.67310
527.17114	535.81641
527.23828	536.26196
527.20483	537.11621
527.24341	539.11426
527.44678	541.43848
518.83496	529.43799
520.23437	530.26929
520.35303	530.45117
520.79395	531.24316
520.50977	532.13086
520.86401	532.86426
520.89648	533.23437
521.01733	535.30737

FLOW ANGLES (DEGREES FROM AXIAL)

RUN NUMBER 61

POINT	ALPHA 1	ALPHA 2	BETA 1
1	70.23701	23.40265	41.91637
2	70.16281	34.40492	32.03058
3	70.15144	36.89117	28.16434
4	70.21237	39.14409	24.29318
5	70.14384	42.75870	18.92877
6	70.15227	46.29941	13.63541
7	70.15292	52.12648	3.98376
8	70.13040	56.51073	-7.39186
9	70.05685	20.88130	39.22562
10	70.13091	27.22986	34.11237
11	70.05336	30.53574	30.74525
12	69.96812	34.12793	26.87900
13	70.04123	41.50076	18.18375
14	69.92375	43.50195	13.63553
15	69.93015	45.93950	8.70869
16	69.92419	50.95045	-0.45223

EFFICIENCIES AND LOSSES

POINT	EFFICIENCY TOTAL STATIC	ZETA ROTOR
1	0.75640	0.34458
2	0.75599	0.29774
3	0.75317	0.27934
4	0.75638	0.25860
5	0.74663	0.24996
6	0.72435	0.26648
7	0.67963	0.29238
8	0.62709	0.30669
9	0.76112	0.29681
10	0.77133	0.26883
11	0.76811	0.25762
12	0.75767	0.25969
13	0.73962	0.26108
14	0.72353	0.25722
15	0.71971	0.24640
16	0.68504	0.26266

BETA 2	DELTA BETA	ABSOLUTE MACH 1	RELATIVE MACH 1
-57.62077	99.53714		
-58.00229	90.03287	0.5365	0.2438
-58.13435	86.29869	0.5232	0.2094
-58.64241	82.93559	0.5208	0.2006
-58.57143	77.50020	0.5197	0.1930
-58.38330	72.01871	0.5186	0.1862
-57.55493	61.53868	0.5165	0.1805
-57.10005	49.70819	0.5175	0.1761
-58.54504	97.77066	0.5172	0.1772
-59.02463	93.13699	0.5910	0.2602
-58.94507	89.69032	0.5837	0.2396
-58.87459	85.75359	0.5825	0.2312
-58.51035	76.69409	0.5782	0.2220
-58.47910	72.11462	0.5776	0.2075
-58.82880	67.53748	0.5732	0.2025
-58.42723	57.97499	0.5736	0.1992
		0.5739	0.1970

ZETA STATOR	BLOCKAGE FACTOR
0.03130	0.91955
0.04280	0.91853
0.04800	0.91860
0.04727	0.91763
0.04776	0.91881
0.04990	0.91956
0.04645	0.91942
0.04851	0.91862
0.05233	0.92131
0.04901	0.91874
0.05302	0.91869
0.05803	0.92018
0.05261	0.92074
0.06621	0.91959
0.06257	0.91975
0.05772	0.92263

REPORT

~~TURBC PROPULSION LABCRATOR~~

REDUCED PERFORMANCE DATA OF TURBINE FR(

TURBINE TYPE MOD II CONFIGURATION RADIAL ROTOR
TEST RUN NO. 62 DATE OF TEST

POINT	PRESSURE RATIO	ISENTROPIC HEAD COEFF. (R=4.125 IN.)	EFFICIENCY TOT-STATIC PERCENT	REFERRED FLOW RATE LBM/SEC
1	1.5023	3.4776	76.72	3.5609
2	1.5048	3.3088	76.45	3.5583
~~3~~	~~1.5046~~	~~3.0792~~	~~77.15~~	~~3.5589~~
4	1.5033	2.8832	77.52	3.5613
5	1.5071	2.7031	76.66	3.5578
6	1.5069	2.5183	76.38	3.5563
~~7~~	~~1.4992~~	~~2.3560~~	~~74.88~~	~~3.5363~~
8	1.4983	2.0748	73.02	3.5339
9	1.5953	3.5853	75.77	3.6888
10	1.5949	3.4016	76.42	3.6867
~~11~~	~~1.6034~~	~~3.3003~~	~~76.16~~	~~3.6903~~
12	1.5997	3.0737	76.68	3.6635
13	1.5978	2.8301	77.68	3.6675
14	1.5944	2.6973	75.91	3.6681
~~15~~	~~1.5964~~	~~2.5502~~	~~75.43~~	~~3.6670~~
16	1.5980	2.3909	76.36	3.6641

/ USNPGS, MONTEREY, CALIF.

JM TESTS WITH TRANSONIC TURBINE TEST RIG

TIP CLEAR.= .033 IN. AXIAL CLEAR. STATOR-ROTOR= 0.410 IN.
/67 DATA REDUCTION METHOD MF

REFERRED TORQUE FT-LB	REFERRED POWER HP	REFERRED SPEED RPM	DEGREE OF REACTION (HUB)	DEGREE OF REACTION (TIP)
22.011	52.862	12616	.0708	.4573
21.419	52.837	12959	.0733	.4629
20.854	53.319	13431	.0782	.4665
20.269	53.505	13866	.0793	.4654
19.446	53.167	14362	.0836	.4706
18.689	52.932	14878	.0854	.4723
17.518	50.990	15290	.0919	.4753
16.009	49.625	16283	.0930	.4798
24.393	61.550	13255	.0890	.4665
23.942	62.003	13604	.0934	.4699
23.652	62.515	13884	.0978	.4739
22.761	62.198	14355	.1009	.4795
22.122	62.926	14942	.0972	.4753
21.065	61.244	15273	.1021	.4809
20.373	60.990	15726	.1063	.4830
19.973	61.817	16258	.1059	.4819

GENERAL RESULTS

VELOCITIES (FT/SEC)
RUN NUMBER 62

POINT	V1	V2	W1
1	715.22217	248.69847	314.91479
2	714.59204	253.26920	306.42358
3	710.02832	256.98926	293.29785
4	708.15186	262.41211	283.50488
5	706.63794	271.43091	273.96948
6	705.51807	281.40283	265.01855
7	699.68237	292.78735	255.66228
8	697.35132	316.92944	245.88350
9	753.99878	266.85229	333.83838
10	750.91260	268.33813	323.60620
11	750.53564	271.78198	317.65674
12	745.29272	273.93774	303.56030
13	744.60132	279.43604	292.82349
14	739.85986	289.19824	284.46313
15	740.08594	298.34155	278.04419
16	749.41089	308.61816	273.91187

TEMPERATURES (DEG R)

POINT	PLENUM TOTAL	STATOR DISCHARGE	ROTOR DISCHARGE
1	564.65625	522.08984	511.87305
2	565.68091	523.18945	512.60791
3	566.36353	524.41309	512.64771
4	567.04590	525.31689	512.90112
5	567.21655	525.66577	512.91553
6	567.21655	525.79736	512.64941
7	567.38696	526.65015	513.76099
8	567.72803	527.26221	514.06348
9	568.92065	521.61353	509.04785
10	569.09106	522.17041	508.70898
11	569.26123	522.38770	508.31250
12	569.43164	523.21069	508.24683
13	569.60181	523.46655	507.56519
14	569.60181	524.05225	508.59595
15	569.60181	524.02441	508.35791
16	569.60181	522.86865	507.06519

W2	U1	U2
469.38354	473.89966	472.17603
468.33228	487.21533	485.44360
474.92993	505.28174	503.44434
477.07617	521.98071	520.08228
475.56299	540.73071	538.76416
475.35547	560.12891	558.09131
466.74561	575.74805	573.65381
465.12573	613.32031	611.08936
510.52954	499.77563	497.95801
514.37427	513.01953	511.15356
517.74780	523.67212	521.76758
519.46899	541.48657	539.51709
523.95703	563.72778	561.67725
514.05591	576.21582	574.12012
512.85913	593.31055	591.15259
512.06860	613.39209	611.16113

ISENTROPIC FROM T1	TOTAL DISCHARGE
505.25928	517.01978
506.00000	517.94556
506.93408	518.14331
507.84839	518.63110
507.78027	519.04614
507.80664	519.23877
508.58521	520.89429
509.02930	522.42163
501.26172	514.97339
501.54053	514.70068
501.21362	514.45898
501.80444	514.49121
502.38281	514.06274
502.68091	515.55542
502.38184	515.76440
501.28149	514.99072

FLOW ANGLES (DEGREES FROM AXIAL)

RUN NUMBER 62

POINT	ALPHA 1	ALPHA 2	BETA 1
1	69.98682	15.93505	38.98843
2	69.95140	19.10094	36.92134
3	69.80698	21.28723	33.31815
4	69.74518	24.16653	30.14674
5	69.68507	28.10490	26.43201
6	69.69858	31.62312	22.53381
7	69.70781	35.89557	18.35512
8	69.64830	41.67209	9.48039
9	69.69820	12.72317	38.40442
10	69.64137	14.50363	36.16985
11	69.57109	15.97250	34.44235
12	69.60191	19.00783	31.16011
13	69.52596	22.28442	27.19753
14	69.47231	26.65961	24.21259
15	69.47182	29.82738	21.03041
16	69.80371	33.19835	19.16924

EFFICIENCIES AND LOSSES

POINT	EFFICIENCY TOTAL STATIC	ZETA ROTOR
1	0.76720	0.26909
2	0.76445	0.27003
3	0.77152	0.23818
4	0.77520	0.21599
5	0.76661	0.22013
6	0.76379	0.21113
7	0.74880	0.22873
8	0.73020	0.22617
9	0.75773	0.26792
10	0.76417	0.24972
11	0.76163	0.24567
12	0.76679	0.22768
13	0.77676	0.19046
14	0.75907	0.21761
15	0.75433	0.22043
16	0.76360	0.21599

BETA 2	DELTA BETA	ABSOLUTE MACH 1	RELATIVE MACH 1
-59.37073	98.35916	0.6384	0.2811
-59.26849	96.18983	0.6371	0.2732
-59.72229	93.04044	0.6323	0.2612
-59.87840	90.02515	0.6301	0.2523
-59.77103	86.20303	0.6286	0.2437
-59.72945	82.26326	0.6275	0.2357
-59.45837	77.81349	0.6218	0.2272
-59.40483	68.88522	0.6194	0.2184
-59.34532	97.74974	0.6733	0.2981
-59.66508	95.83493	0.6702	0.2888
-59.69081	94.13316	0.6697	0.2834
-60.09337	91.25348	0.6645	0.2707
-60.43001	87.62753	0.6637	0.2610
-59.81644	84.02902	0.6591	0.2534
-59.69121	80.72162	0.6593	0.2477
-59.71388	78.88312	0.6684	0.2443

ZETA STATOR	BLOCKAGE FACTOR
0.06139	0.91992
0.06300	0.91973
0.07039	0.92149
0.07471	0.92258
0.07808	0.92191
0.07845	0.92225
0.07713	0.92191
0.07893	0.92272
0.07217	0.92530
0.07446	0.92622
0.07992	0.92603
0.08320	0.92182
0.08819	0.92205
0.08921	0.92498
0.08676	0.92522
0.06660	0.92370

REPORT

TURBO PROPULSION LABORATORY

REDUCED PERFORMANCE DATA OF TURBINE FR(

TURBINE TYPE MOD II CONFIGURATION RADIAL ROTOR
TEST RUN NO. 63 DATE OF TEST

POINT	PRESSURE RATIO	ISENTROPIC HEAD COEFF. (R=4.125 IN.)	EFFICIENCY TOT-STATIC PERCENT	REFERRED FLOW RATE LBM/SEC
1	1.3007	3.4783	76.71	3.1504
2	1.3015	3.2664	77.86	3.1495
3	1.3048	2.7577	77.42	3.1442
4	1.3075	2.3948	76.35	3.1327
5	1.2987	2.0136	74.25	3.1046
FOR POINTS 1 TO 5 AVG. PRESSURE RATIO= 1.3027 , MAX.(				
6	1.4026	3.4619	77.02	3.3849
7	1.4044	2.9993	78.03	3.3822
8	1.4047	2.6020	77.25	3.3617
9	1.4035	2.2521	75.87	3.3687
10	1.4023	1.9555	72.74	3.3585
FOR POINTS 6 TO 10 AVG. PRESSURE RATIO= 1.4035 , MAX.(				
11	1.4495	3.4043	76.54	3.4814
12	1.4509	3.0194	78.31	3.4830
13	1.4551	2.6752	77.04	3.4728
14	1.4561	2.3154	74.37	3.4695
15	1.4538	2.0025	73.04	3.4576
FOR POINTS 11 TO 15 AVG. PRESSURE RATIO= 1.4531 , MAX.(				
16	1.5008	3.4617	76.63	3.5647
17	1.5014	3.1200	77.67	3.5570
18	1.5008	2.8842	77.31	3.5532
19	1.5031	2.7103	76.12	3.5477
20	1.5064	2.2436	74.49	3.5238
FOR POINTS 16 TO 20 AVG. PRESSURE RATIO= 1.5025 , MAX.(				
21	1.5991	3.5930	75.76	3.6748
22	1.6020	3.1133	75.45	3.6735
23	1.6045	2.7438	76.21	3.6656
24	1.5950	2.4286	75.37	3.6494
25	1.5919	1.9371	72.09	3.6447
FOR POINTS 21 TO 25 AVG. PRESSURE RATIO= 1.5985 , MAX.(				

(USNPGS, MONTEREY, CALIF.

)M TESTS WITH TRANSONIC TURBINE TEST RIG

TIP CLEAR.= .033 IN. AXIAL CLEAR. STATOR-ROTOR= 1.500 IN.
/67 DATA REDUCTION METHOD MF

REFERRED TORQUE FT-LB	REFERRED POWER HP	REFERRED SPEED RPM	DEGREE OF REACTION (HUB)	DEGREE OF REACTION (TIP)
15.812	30.830	10243	.0310	.4506
15.565	31.351	10581	.0309	.4522
14.262	31.410	11569	.0334	.4582
13.108	31.095	12461	.0304	.4660
11.442	29.237	13423	.0254	.4672

)EVIATION +0.374 PCT. -0.304 PCT., PAVG./PATMO= 1.1238

19.201	42.343	11584	.0113	.4636
18.125	43.018	12468	.0225	.4710
16.617	42.357	13390	.0303	.4780
15.196	41.585	14376	.0269	.4784
13.519	39.655	15409	.0427	.4797

)EVIATION +0.086 PCT. -0.086 PCT., PAVG./PATMO= 1.1639

20.339	47.266	12208	.0226	.4695
19.630	48.500	12979	.0307	.4738
18.190	47.923	13839	.0406	.4800
16.336	46.304	14889	.0455	.4833
14.839	45.137	15978	.0466	.4858

)EVIATION +0.209 PCT. -0.248 PCT., PAVG./PATMO= 1.1980

21.932	52.733	12630	.0328	.4747
21.068	53.383	13310	.0395	.4794
20.132	53.029	13837	.0424	.4844
19.219	52.317	14299	.0460	.4860
17.040	51.111	15757	.0562	.4898

)EVIATION +0.261 PCT. -0.114 PCT., PAVG./PATMO= 1.1978

24.380	61.596	13272	.0533	.4851
22.636	61.549	14283	.0628	.4913
21.448	62.218	15238	.0679	.4970
19.751	60.542	16102	.0721	.4990
16.817	57.603	17993	.0721	.4999

)EVIATION +0.376 PCT. -0.416 PCT., PAVG./PATMO= 1.1652

GENERAL RESULTS

VELOCITIES (FT/SEC)
RUN NUMBER 63

POINT	V1	V2	W1
1	599.80225	204.33617	271.01782
2	599.29321	207.25876	262.68677
3	593.96021	223.02359	237.35219
4	591.08081	239.78516	220.21400
5	585.03369	267.08325	204.50685
6	671.88428	229.73703	300.22021
7	665.81982	238.98238	275.39111
8	659.02783	253.92865	252.84639
9	655.41187	276.80933	237.17805
10	654.32983	307.56104	226.79066
11	694.42310	241.86237	305.36865
12	690.00879	247.13632	285.30640
13	688.06274	263.80029	266.98853
14	683.89258	290.85718	249.54605
15	684.69873	317.81226	238.94762
16	722.52148	252.07901	318.82593
17	720.61060	258.10571	301.82422
18	717.70776	266.53882	288.50977
19	714.96558	276.57593	278.60767
20	712.58765	306.99780	255.44917
21	764.07983	269.23315	339.08252
22	762.33252	282.63062	314.94678
23	755.33618	292.16553	292.88940
24	748.55103	308.01392	275.62720
25	748.67236	356.88013	260.53735

TEMPERATURES (DEG R)

POINT	PLENUM TOTAL	STATOR DISCHARGE	ROTOR DISCHARGE
1	561.91992	531.98340	527.19531
2	562.09106	532.20532	526.71948
3	562.26221	532.90601	526.20239
4	562.26221	533.18994	525.76196
5	562.43335	533.95288	526.39697
6	566.02246	528.45825	521.39282
7	566.70483	529.81567	520.99146
8	567.21655	531.07617	521.23560
9	567.38696	531.64209	521.20752
10	567.38696	531.76001	521.44409
11	569.43164	529.30493	520.62939
12	570.11230	530.49414	519.91577
13	570.45264	531.05762	519.92651
14	570.79272	531.87378	520.46265
15	570.79272	531.78198	520.04321
16	572.66235	529.22266	519.23242
17	572.83203	529.62183	518.43237
18	573.17163	530.30884	518.64722
19	573.30737	530.77148	518.89600
20	573.68091	531.42749	518.55078
21	576.73193	528.15137	515.76318
22	577.40894	529.05029	515.78296
23	577.57812	530.10303	514.76367
24	577.74731	531.12134	515.38525
25	577.91650	531.27539	515.41235

W2	U1	U2
360.44604	383.81982	382.42383
365.77075	396.55981	395.11743
368.14526	433.66431	432.08691
369.01855	467.09790	465.39893
361.64355	503.23047	501.40039
416.72778	435.67969	434.09497
424.60278	469.18506	467.47876
424.66846	504.13013	502.29687
423.70264	541.30664	539.33789
415.88330	580.21045	578.10010
442.68164	460.51196	458.83716
454.73291	489.87891	488.09692
450.62939	522.52051	520.62012
443.97168	562.32422	560.27881
442.17969	603.45923	601.26465
469.09521	477.78638	476.04883
472.99683	503.59033	501.75879
470.52148	523.67212	521.76758
467.12622	541.23462	539.26611
466.27759	596.58545	594.41553
511.86743	503.84229	502.00977
506.45068	542.56641	540.59302
517.38916	578.91504	576.80908
512.21045	611.80859	609.58325
505.09326	683.78613	681.29907

ISENTROPIC FROM T1	TOTAL DISCHARGE
521.98608	530.66968
522.14966	530.29395
522.55981	530.34131
522.64941	530.54639
523.74341	532.33276
515.67554	525.78467
516.47827	525.74390
517.31616	526.60107
517.97485	527.58350
517.71021	529.31543
514.71582	525.49707
515.48877	524.99805
515.46484	525.71729
515.99438	527.50220
515.87280	528.44800
512.73169	524.52002
512.75537	523.97583
513.19409	524.55884
513.41626	525.26123
513.53247	526.39331
507.90332	521.79492
508.13843	522.42993
508.69580	521.86670
509.74414	523.27979
509.95190	526.01050

FLOW ANGLES (DEGREES FROM AXIAL)

RUN NUMBER 63

POINT	ALPHA 1	ALPHA 2	BETA 1
1	70.35411	21.81581	41.92059
2	70.26996	23.49132	39.63066
3	70.13914	31.57175	31.76971
4	70.05412	38.16563	23.70363
5	70.10789	45.78113	13.25702
6	70.27859	19.79764	40.95773
7	70.13554	25.26402	34.76161
8	70.03391	32.33392	27.12646
9	69.89589	39.01917	18.22337
10	69.96709	46.00826	8.75763
11	70.00932	19.21899	38.97495
12	69.85732	22.55379	33.60999
13	69.88042	30.05518	27.56607
14	69.75966	38.16559	18.53770
15	69.86665	44.31706	9.49098
16	69.97151	16.98639	39.09148
17	69.94691	21.43475	35.04967
18	69.94304	25.99173	31.44464
19	69.83475	29.98824	27.79214
20	69.89735	39.09709	16.50908
21	69.82234	13.36659	38.98969
22	69.79715	22.23427	33.28943
23	69.63574	26.49768	26.17813
24	69.63120	32.92389	19.04431
25	69.68765	43.77295	4.03426

EFFICIENCIES AND LOSSES

POINT	EFFICIENCY TOTAL STATIC	ZETA ROTOR
1	0.76711	0.32890
2	0.77860	0.29529
3	0.77419	0.24985
4	0.76349	0.22259
5	0.74248	0.20502
6	0.77020	0.28754
7	0.78033	0.23647
8	0.77255	0.21348
9	0.75871	0.18583
10	0.72745	0.21481
11	0.76544	0.27035
12	0.78314	0.20993
13	0.77039	0.21496
14	0.74375	0.22123
15	0.73038	0.21251
16	0.76629	0.26608
17	0.77667	0.23849
18	0.77309	0.23372
19	0.76119	0.23754
20	0.74487	0.22437
21	0.75761	0.26876
22	0.75455	0.26821
23	0.76205	0.21966
24	0.75367	0.21183
25	0.72087	0.21292

BETA 2	DELTA BETA	ABSOLUTE MACH 1	RELATIVE MACH 1
-58.24429	100.16489		
-58.68962	98.32028	0.5303	0.2396
-58.92661	90.69632	0.5298	0.2322
-59.27724	82.98087	0.5247	0.2097
-58.99927	72.25629	0.5220	0.1945
-58.75459	99.71233	0.5163	0.1805
-59.40259	94.16420	0.5961	0.2663
-59.65327	86.77974	0.5899	0.2440
-59.49716	77.72054	0.5832	0.2238
-59.09282	67.85045	0.5797	0.2098
-58.94185	97.91679	0.5787	0.2006
-59.87349	93.48347	0.6156	0.2707
-59.55618	87.12225	0.6110	0.2526
-58.99731	77.53502	0.6089	0.2363
-59.05276	68.54373	0.6048	0.2207
-59.07402	98.16550	0.6055	0.2113
-59.47330	94.52296	0.6405	0.2826
-59.39073	90.83537	0.6386	0.2675
-59.14833	86.94048	0.6356	0.2555
-59.27144	75.78052	0.6329	0.2466
-59.22063	98.21031	0.6304	0.2260
-58.89775	92.18718	0.6781	0.3009
-59.64388	85.82201	0.6759	0.2792
-59.68437	78.72868	0.6691	0.2594
-59.32286	63.35712	0.6624	0.2439
		0.6624	0.2305

ZETA STATOR	BLOCKAGE FACTOR
0.02664	0.92070
0.02970	0.92006
0.05045	0.91738
0.06335	0.91275
0.06213	0.91172
0.04920	0.91180
0.05926	0.91357
0.07057	0.91068
0.08052	0.91274
0.07120	0.91386
0.06431	0.91631
0.07192	0.91831
0.07455	0.91655
0.08278	0.91673
0.07474	0.91534
0.06435	0.91847
0.06332	0.91821
0.06542	0.91889
0.07275	0.91748
0.07554	0.91241
0.07311	0.91855
0.07180	0.91988
0.08486	0.91898
0.08705	0.91865
0.08278	0.91857

REPORT

TURBC PROPULSICN LABGRATOR

REDUCED PERFCRMANCE DATA OF TURBINE FR

TURBINE TYPE MOD II CONFIGURATION RADIAL ROTOR
TEST RUN NO. 68 DATE OF TEST

POINT	PRESSURE RATIO	ISENTROPIC HEAD COEFF. (R=4.125 IN.)	EFFICIENCY TOT-STATIC PERCENT	REFERRED FLOW RATE LBM/SEC
1	1.4012	3.3991	79.42	3.3381
2	1.3974	2.9410	79.21	3.3155
3	1.3961	2.7556	79.15	3.3193
4	1.3971	2.5491	78.48	3.3103
5	1.3986	2.3906	78.07	3.3128
6	1.3996	2.2443	77.37	3.3049
7	1.4008	1.9527	75.28	3.3094
8	1.4006	1.7445	72.28	3.3110

FOR POINTS 1 TO 8 AVG. PRESSURE RATIO= 1.3989 , MAX.

POINT	PRESSURE RATIO	ISENTROPIC HEAD COEFF. (R=4.125 IN.)	EFFICIENCY TOT-STATIC PERCENT	REFERRED FLOW RATE LBM/SEC
9	1.3038	3.4288	78.40	3.1050
10	1.3052	3.0258	78.73	3.1060
11	1.2984	2.7233	78.40	3.0653
12	1.2989	2.5180	78.01	3.0682
13	1.2980	2.1512	77.20	3.0640
14	1.2998	1.8816	75.23	3.0637
15	1.2996	1.6441	71.37	3.0604
16	1.2987	1.4268	66.08	3.0562

FOR POINTS 9 TO 16 AVG. PRESSURE RATIO= 1.3003 , MAX.

POINT	PRESSURE RATIO	ISENTROPIC HEAD COEFF. (R=4.125 IN.)	EFFICIENCY TOT-STATIC PERCENT	REFERRED FLOW RATE LBM/SEC
17	1.4995	3.3379	81.12	3.5083
18	1.5026	3.1003	80.73	3.5074
19	1.5030	2.8956	79.50	3.5053
20	1.5030	2.6951	80.31	3.5036
21	1.5066	2.5572	80.28	3.4987
22	1.5034	2.3785	78.39	3.4993
23	1.5047	2.1211	76.76	3.4934
24	1.5028	1.8661	74.08	3.4869

FOR POINTS 17 TO 24 AVG. PRESSURE RATIO= 1.5032 , MAX.

CONTD. ON SHEE

:Y USNPGS, MONTEREY, CALIF.

OM TESTS WITH TRANSONIC TURBINE TEST RIG

TIP CLEAR.= .015 IN. AXIAL CLEAR. STATOR-ROTOR= 1.000 IN.
/67 DATA REDUCTION METHOD MF

REFERRED TORQUE FT-LB	REFERRED POWER HP	REFERRED SPEED RPM	DEGREE OF REACTION (HUB)	DEGREE OF REACTION (TIP)
19.320	42.937	11674	.0582	.5260
17.734	42.206	12502	.0676	.5277
17.150	42.113	12899	.0711	.5276
16.328	41.731	13425	.0744	.5312
15.766	41.672	13885	.0797	.5328
15.118	41.281	14344	.0829	.5328
13.755	40.317	15397	.0860	.5364
12.487	38.717	16287	.0849	.5374

DEVIATION +0.162 PCT. -0.203 PCT., PAVG./PATMO= 1.1662

15.880	31.317	10360	.0403	.5091
15.015	31.584	11050	.0457	.5143
13.866	30.452	11537	.0591	.5168
13.289	30.373	12006	.0604	.5175
12.124	29.945	12974	.0675	.5219
11.076	29.324	13907	.0671	.5246
9.608	27.769	14873	.0644	.5246
8.437	25.612	15946	.0631	.5232

DEVIATION +0.377 PCT. -0.173 PCT., PAVG./PATMO= 1.1281

22.414	54.827	12849	.0784	.5363
21.545	54.815	13365	.0856	.5386
20.500	53.984	13833	.0883	.5406
19.968	54.504	14339	.0910	.5431
19.469	54.705	14760	.0980	.5469
18.292	53.168	15268	.0964	.5459
16.904	52.079	16183	.0999	.5492
15.253	50.026	17229	.0998	.5525

DEVIATION +0.223 PCT. -0.247 PCT., PAVG./PATMO= 1.2035

T 2

REPORT

TURBC PROPULSION LABCRATOR

RECUCED PERFCRMANCE DATA OF TURBINE FR

TURBINE TYPE MCC II CONFIGURATION RADIAL ROTOR

TEST RUN NO. 68 DATE OF TEST

POINT	PRESSURE RATIO	ISENTRCPIC HEAD COEFF. (R=4.125 IN.)	EFFICIENCY TOT-STATIC PERCENT	REFERRED FLOW RATE LBM/SEC
25	1.5964	3.4941	78.04	3.6313
26	1.5937	3.3098	78.06	3.6293
27	1.5923	3.0803	78.42	3.6209
28	1.5923	2.9009	78.75	3.6183
29	1.5954	2.6886	79.07	3.6155
30	1.5945	2.5616	78.48	3.6095
31	1.5968	2.3887	77.49	3.6126
32	1.6045	2.0977	74.39	3.6146

FOR POINTS 25 TC 32 AVG. PRESSURE RATIO= 1.5957 , MAX.

Y USNPGS, MONTEREY, CALIF.

OM TESTS WITH TRANSONIC TURBINE TEST RIG

TIP CLEAR.= .015 IN. AXIAL CLEAR. STATOR-ROTOR= 1.000 IN.
/67 DATA REDUCTION METHOD MF

REFERRED TORQUE FT-LB	REFERRED POWER HP	REFERRED SPEED RPM	DEGREE OF REACTION (HUB)	DEGREE OF REACTION (TIP)
24.431	62.486	13435	.0985	.5501
23.730	62.255	13781	.1031	.5511
22.925	62.290	14273	.1075	.5510
22.325	62.508	14708	.1119	.5548
21.606	62.958	15307	.1115	.5568
20.885	62.312	15673	.1158	.5594
19.959	61.754	16253	.1198	.5583
18.052	59.891	17428	.1210	.5653

DEVIATION +0.550 PCT. -0.214 PCT., PAVG./PATMO= 1.1675

GENERAL RESULTS

VELOCITIES (FT/SEC)
RUN NUMBER 68

POINT	V1	V2	W1
1	629.60229	215.74159	267.49707
2	623.66309	220.52319	246.61536
3	617.85425	224.84474	238.26138
4	614.05078	230.92804	229.08687
5	614.05322	238.47234	224.41199
6	613.24048	246.26219	220.55176
7	613.50122	270.03633	218.75084
8	615.85913	297.00098	221.20448
9	570.22510	192.38498	246.26828
10	566.71802	197.88794	230.00241
11	553.34839	200.79482	213.05516
12	555.04248	209.93118	207.71129
13	549.04199	225.56129	197.04674
14	551.02100	246.13707	196.14902
15	550.16846	274.92139	199.72488
16	555.23804	311.73022	211.06706
17	680.07227	236.39636	283.84180
18	679.10522	239.04375	273.14209
19	676.49731	244.73845	263.70605
20	670.43311	246.50630	254.01537
21	663.19727	247.90678	247.53049
22	674.03149	264.55005	244.68663
23	669.47168	281.03784	238.47722
24	666.45630	306.07910	238.95050
25	734.73047	259.53955	312.17017
26	711.12256	258.61084	292.02783
27	711.84619	260.58325	282.95898
28	705.03564	261.80762	272.61816
29	720.78149	271.19287	269.84473
30	698.50732	269.22217	259.25537
31	712.76465	265.03906	257.56738
32	703.59644	307.06958	253.25223

W2	U1	U2
466.39575	439.06250	437.46582
459.32959	470.19287	468.48267
462.93481	485.12817	483.36377
462.83032	504.92212	503.08545
463.08691	522.19653	520.29736
462.55273	539.47119	537.50903
461.38721	579.05884	576.95264
455.13452	612.52856	610.30078
400.14893	389.03833	387.62329
401.92041	414.95020	413.44092
401.42383	433.30420	431.72852
399.11694	450.93872	449.29883
404.11377	487.28760	485.51514
403.04395	522.34082	520.44067
400.40747	558.61719	556.58545
392.31030	598.88867	596.71045
526.73828	483.68872	481.92920
525.12646	503.84229	502.00977
517.70239	521.51294	519.61621
528.22046	541.05469	539.08691
537.64966	556.96191	554.93604
513.98779	576.03564	573.94067
514.83276	610.65674	608.43579
511.35767	649.92090	647.55688
543.21289	507.87305	506.02588
560.84717	521.00903	519.11426
557.78882	539.61523	537.65259
564.42456	556.13403	554.11133
552.29590	578.87891	576.77368
569.02197	592.62646	590.47119
552.05371	614.57959	612.34424
554.50195	658.88208	656.48560

TEMPERATURES (DEG R)

POINT	PLENUM TOTAL	STATOR DISCHARGE	ROTOR DISCHARGE
1	566.02246	533.03735	520.77441
2	566.02246	533.65674	521.02759
3	566.02246	534.25684	521.00537
4	566.02246	534.64673	521.03467
5	566.02246	534.64648	520.82764
6	566.02246	534.72949	520.79761
7	566.02246	534.70288	520.76807
8	566.02246	534.46167	521.06934
9	564.31445	537.25757	528.88892
10	564.31445	537.58936	528.44531
11	564.48535	539.00635	529.26123
12	564.48535	538.85010	529.06201
13	564.48535	539.40137	528.89966
14	564.48535	539.22021	528.73950
15	564.48535	539.29834	529.08813
16	564.48535	538.83203	529.51538
17	567.04590	528.56055	512.03564
18	568.75049	530.37451	513.48291
19	568.75049	530.66870	513.98877
20	569.77197	532.36987	514.34448
21	569.77197	533.17285	514.03003
22	569.60181	531.79712	514.59546
23	569.77197	532.47705	514.92847
24	569.43164	532.47192	515.20898
25	571.81274	526.89258	510.29150
26	571.98267	529.90283	510.66089
27	571.98267	529.81714	510.41406
28	572.15259	530.79004	510.27832
29	572.32251	529.09180	509.56616
30	572.15259	531.55249	509.99023
31	572.15259	529.87817	509.81030
32	571.98267	530.78882	510.27808

ISENTROPIC FROM T1	TOTAL DISCHARGE
517.36523	524.64746
517.82983	525.07422
518.37671	525.21216
518.54492	525.47217
518.31958	525.55981
518.28784	525.84399
518.04956	526.83594
517.82202	528.40942
525.64844	531.96875
525.70923	531.70386
527.02710	532.61621
526.81641	532.72925
527.15942	533.13330
526.86670	533.78076
527.00537	535.37744
526.63403	537.60156
508.84595	516.68579
510.21240	518.23779
510.33643	518.97290
511.81763	519.40088
512.14160	519.14404
511.00757	520.41919
511.40747	521.50073
511.36719	523.00464
502.90137	515.89673
505.68408	516.22607
505.51221	516.06445
506.16162	515.98193
504.37305	515.68604
506.51904	516.02148
504.75732	516.57104
505.05298	518.12427

FLOW ANGLES (DEGREES FROM AXIAL)

RUN NUMBER 68

POINT	ALPHA 1	ALPHA 2	BETA 1
1	69.42986	6.20296	34.21100
2	69.46504	16.04895	27.49147
3	69.17795	18.75490	22.81136
4	69.15904	23.38173	17.51694
5	69.16827	27.12178	13.32352
6	69.18079	30.81245	8.79677
7	69.11861	38.25180	-1.53297
8	69.25374	44.37505	-9.52449
9	69.60263	10.48623	36.19571
10	69.47099	17.26091	30.22377
11	69.29149	22.22058	23.30597
12	69.30286	27.34261	19.19214
13	69.15773	34.25801	7.53149
14	69.16222	41.27179	-2.15077
15	69.26352	47.33690	-12.75304
16	69.37051	53.57162	-22.05447
17	69.41624	2.68796	32.61002
18	69.36816	7.99896	28.82887
19	69.30685	14.08164	24.97464
20	69.08856	15.79937	19.60223
21	68.80219	16.97816	14.35310
22	69.27106	26.43953	12.83670
23	69.17560	32.57431	3.62586
24	69.13222	39.38423	-6.53154
25	69.78142	6.19440	35.56900
26	69.01720	4.65913	29.30998
27	69.13025	9.41667	26.33563
28	68.98698	11.33125	21.97546
29	69.53262	18.87099	20.93111
30	68.80513	17.83009	13.07067
31	69.27347	25.71196	11.66002
32	68.90446	32.69691	-0.55185

BETA 2	DELTA BETA	ABSOLUTE MACH 1	RELATIVE MACH 1
-62.62163	96.83263	0.5561	0.2363
-62.52338	90.01485	0.5506	0.2177
-62.61900	85.43036	0.5451	0.2102
-62.74347	80.26041	0.5416	0.2021
-62.72014	76.04366	0.5416	0.1979
-62.79019	71.58694	0.5408	0.1945
-62.63774	61.10477	0.5411	0.1929
-62.19701	52.67252	0.5433	0.1951
-61.78676	97.98247	0.5017	0.2167
-61.95386	92.17763	0.4985	0.2023
-62.41530	85.72127	0.4861	0.1872
-62.14575	81.33789	0.4876	0.1825
-62.52715	70.05862	0.4821	0.1730
-62.67790	60.52711	0.4839	0.1723
-62.27017	49.51712	0.4832	0.1754
-61.84566	39.79118	0.4878	0.1854
-63.36536	95.97537	0.6033	0.2518
-63.20601	92.03488	0.6014	0.2419
-62.70741	87.68205	0.5989	0.2335
-63.31770	82.91994	0.5926	0.2245
-63.83243	78.18552	0.5857	0.2186
-62.55699	75.39368	0.5961	0.2164
-62.61212	66.23798	0.5917	0.2108
-62.44278	55.91122	0.5890	0.2112
-61.64087	97.20987	0.6528	0.2774
-62.63971	91.94969	0.6300	0.2587
-62.55627	88.89191	0.6307	0.2507
-62.94745	84.92291	0.6241	0.2413
-62.31339	83.24449	0.6391	0.2392
-63.23022	76.30089	0.6179	0.2293
-62.27673	73.93674	0.6315	0.2282
-62.22345	61.67159	0.6228	0.2242

REPORT

TURBO PROPULSION LABORATORY

REDUCED PERFORMANCE DATA OF TURBINE FRC

TURBINE TYPE MOD II CONFIGURATION RADIAL ROTOR T
TEST RUN NO. 77 DATE OF TEST

POINT	PRESSURE RATIO	ISENTROPIC HEAD COEFF. (R=4.125 IN.)	EFFICIENCY TOT-STATIC PERCENT	REFERRED FLOW RATE LBM/SEC
1	1.2988	3.0431	80.88	3.1039
2	1.3011	2.5106	79.16	3.0898
3	1.3008	1.8738	75.68	3.0719
4	1.2991	1.3709	63.49	3.0765
FOR POINTS 1 TO 4 AVG. PRESSURE RATIO= 1.2999 , MAX.D				
5	1.4012	2.9253	80.13	3.3456
6	1.3986	2.5898	78.78	3.3330
7	1.3992	2.1042	77.27	3.3292
8	1.4002	1.7431	73.96	3.3288
FOR POINTS 5 TO 8 AVG. PRESSURE RATIO= 1.3998 , MAX.D				
9	1.2991	3.0499	80.36	3.0987
10	1.3004	2.4977	79.12	3.0776
11	1.3011	1.8770	75.54	3.0677
12	1.2988	1.3682	64.84	3.0758
FOR POINTS 9 TO 12 AVG. PRESSURE RATIO= 1.2998 , MAX.C				
13	1.4009	2.9053	79.37	3.3478
14	1.4012	2.5888	81.02	3.3410
15	1.3982	2.1028	79.40	3.3254
16	1.3989	1.7436	73.69	3.3250
FOR POINTS 13 TO 16 AVG. PRESSURE RATIO= 1.3998 , MAX.C				

USNPGS, MONTEREY, CALIF.

IM TESTS WITH TRANSONIC TURBINE TEST RIG

IP CLEAR.= .015 IN. AXIAL CLEAR. STATOR-ROTOR= 0.410 IN.
8/09 DATA REDUCTION METHOD MF

REFERRED TORQUE FT-LB	REFERRED POWER HP	REFERRED SPEED RPM	DEGREE OF REACTION (HUB)	DEGREE OF REACTION (TIP)
15.320	31.846	10920	.0791	.4697
13.602	31.232	12062	.0881	.4809
11.165	29.661	13955	.0930	.4891
8.004	24.802	16277	.0790	.4894

EVIATION +0.090 PCT. -0.090 PCT., PAVG./PATMO= 1.3001

18.124	43.420	12585	.0983	.4860
16.657	42.298	13339	.1054	.4898
14.720	41.496	14808	.1098	.4982
12.835	39.795	16287	.1096	.5030

EVIATION +0.101 PCT. -0.089 PCT., PAVG./PATMO= 1.4000

15.220	31.618	10913	.0536	.4894
13.494	31.034	12081	.0630	.4985
11.143	29.590	13950	.0749	.5052
8.160	25.299	16285	.0633	.4988

EVIATION +0.096 PCT. -0.083 PCT., PAVG./PATMO= 1.3000

17.897	43.008	12624	.0763	.5022
17.214	43.83[illegible]	13377	.0818	.5093
15.088	42.505	14798	.0907	.5136
12.758	39.497	16262	.0915	.5153

EVIATION +0.101 PCT. -0.113 PCT., PAVG./PATMO= 1.4000

GENERAL RESULTS

VELOCITIES (FT/SEC)
RUN NUMBER 77

POINT	V1	V2	W1
1	597.13525	204.92401	250.02606
2	592.03052	227.75537	223.17967
3	589.87573	274.98022	197.69690
4	589.99756	356.32886	203.44823
5	663.16846	234.80237	267.52051
6	659.09692	251.06436	249.45665
7	656.36011	282.94702	227.17372
8	657.43433	323.28101	218.57817
9	597.68286	205.78839	250.05664
10	594.06396	228.95029	223.77377
11	590.47974	275.38525	198.11826
12	589.22388	350.74365	204.17590
13	661.61597	237.10893	266.39404
14	660.47095	244.08421	250.21523
15	655.28418	274.53711	227.03908
16	654.52490	321.71631	218.29687

TEMPERATURES (DEG R)

POINT	PLENUM TOTAL	STATOR DISCHARGE	ROTOR DISCHARGE
1	565.68091	536.01001	529.20361
2	565.68091	536.51514	528.86987
3	565.51025	536.55640	528.18848
4	565.51025	536.54443	529.03662
5	568.58008	531.98413	522.05762
6	568.58008	532.43213	522.32935
7	568.58008	532.73169	521.64380
8	568.75049	532.78467	521.41479
9	564.82715	535.10181	528.55103
10	565.16870	535.80225	528.41992
11	565.33936	536.32617	528.03955
12	565.51025	536.62036	528.84058
13	567.55762	531.13281	521.44434
14	567.89844	531.59961	520.59375
15	568.23926	532.50830	520.69189
16	568.58008	532.93188	521.58521

W2	U1	U2
378.26514	410.55957	409.06641
374.42065	453.49414	451.84473
371.00781	524.60791	522.69971
359.02148	611.88037	609.65527
434.99902	474.36743	472.64209
426.38208	502.79883	500.96997
427.30835	558.18555	556.15527
426.23340	614.00391	611.77075
374.20850	409.98364	408.49243
370.53052	454.03418	452.38281
369.91821	524.31982	522.41309
363.95093	612.20459	609.97778
430.99390	475.41138	473.68213
439.34595	503.95044	502.11743
437.36938	557.64551	555.61743
425.77441	612.99634	610.76685

ISENTROPIC FROM T1	TOTAL DISCHARGE
524.67725	532.69800
524.68530	533.18628
524.47168	534.48047
524.78345	539.60205
516.44531	526.64526
516.70288	527.57446
516.63940	528.30566
516.53638	530.11133
523.85767	532.07495
524.12695	532.78174
524.24683	534.35010
524.97339	539.07739
515.72974	526.12256
515.85083	525.55127
516.51123	526.96362
516.83374	530.19775

EFFICIENCIES AND LOSSES

PCINT	EFFICIENCY TOTAL STATIC	ZETA ROTOR
1	0.79421	0.16303
2	0.79215	0.15949
3	0.79153	0.13448
4	0.78483	0.12917
5	0.78073	0.13027
6	0.77374	0.13108
7	0.75281	0.14156
8	0.72281	0.16774
9	0.78400	0.20005
10	0.78730	0.17443
11	0.78399	0.14899
12	0.78010	0.15160
13	0.77202	0.12174
14	0.75231	0.13100
15	0.71365	0.14548
16	0.66077	0.19479
17	0.81116	0.12610
18	0.80728	0.12984
19	0.79502	0.14613
20	0.80306	0.10431
21	0.80279	0.07945
22	0.78386	0.14700
23	0.76763	0.14520
24	0.74085	0.15846
25	0.78038	0.23508
26	C.78059	0.16416
27	0.78418	0.16397
28	0.78749	0.13967
29	0.79071	0.17531
30	0.78477	0.12027
31	0.77488	0.17236
32	0.74390	0.17660

ZETA STATOR	BLOCKAGE FACTOR
0.09698	0.92208
0.10027	0.92046
0.11265	0.92302
0.12102	~~0.92137~~
0.11940	0.92263
0.12145	0.92055
0.11854	0.92254
0.11148	~~0.92309~~
0.08917	0.92020
0.09726	0.92162
0.11356	0.91948
0.10813	~~0.92036~~
0.11815	0.92262
0.11460	0.92146
0.11846	0.92003
0.10157	~~0.91898~~
0.09487	0.92458
0.09850	0.92485
0.10283	0.92508
0.11710	~~0.92569~~
0.13388	0.92508
0.10253	0.92603
0.11203	0.92536
0.11479	~~0.92513~~
0.06009	0.92781
0.11329	0.92916
0.10734	0.92819
0.11920	0.92910
0.08194	0.92775
0.13217	0.92782
0.09717	0.92838
0.12248	0.92815

FLOW ANGLES (DEGREES FROM AXIAL)

RUN NUMBER 77

POINT	ALPHA 1	ALPHA 2	BETA 1
1	70.64803	23.27373	37.68272
2	70.55841	34.25290	28.00095
3	70.68813	47.27664	9.33776
4	70.61951	58.32417	-15.77644
5	70.54552	23.72371	34.34760
6	70.55617	31.70511	28.41600
7	70.51382	41.07169	15.46605
8	70.58885	48.68642	1.58891
9	70.78671	24.29871	38.13335
10	70.65186	35.32518	28.41360
11	70.67889	47.43404	9.56007
12	70.55273	57.93956	-16.09290
13	70.44252	24.97395	33.75851
14	70.51901	28.95685	28.32239
15	70.47787	39.19341	15.31537
16	70.52094	48.70358	1.06723

EFFICIENCIES AND LOSSES

POINT	EFFICIENCY TOTAL STATIC	ZETA ROTOR
1	0.80879	0.27991
2	0.79159	0.26974
3	0.75685	0.25319
4	0.63490	0.29460
5	0.80130	0.26744
6	0.78778	0.27643
7	0.77268	0.25472
8	0.73959	0.25249
9	0.80359	0.29153
10	0.79116	0.27886
11	0.75538	0.25798
12	0.64837	0.27082
13	0.79371	0.27460
14	0.81015	0.23363
15	0.79398	0.21535
16	0.73688	0.24814

BETA 2	DELTA BETA	ABSOLUTE MACH 1	RELATIVE MACH 1
-60.15440	97.83713	0.5260	0.2202
-59.81540	87.81635	0.5213	0.1965
-59.81097	69.14873	0.5193	0.1741
-58.58897	42.81253	0.5195	0.1791
-60.38536	94.73296	0.5864	0.2365
-59.93703	88.35303	0.5825	0.2205
-60.05315	75.51918	0.5799	C.2007
-59.95233	61.54124	0.5809	0.1931
-59.91971	98.05305	0.5269	0.2205
-59.72617	88.13977	0.5234	0.1972
-59.76328	69.32333	0.5200	0.1745
-59.23282	43.13992	0.5187	0.1798
-60.08556	93.84407	0.5855	0.2357
-60.91484	89.23723	0.5842	0.2213
-60.89053	76.20590	0.5791	0.2007
-60.08833	61.15556	0.5782	0.1928

ZETA STATOR	BLOCKAGE FACTOR
-0.00774	0.92366
0.00189	0.92199
-0.00140	0.92010
0.00281	0.91992
0.00556	0.92327
0.00497	0.92370
0.00521	0.92511
0.00085	0.92544
-0.00734	0.92084
-0.00371	0.91763
-0.00240	0.91838
0.00811	0.91881
0.01053	0.92322
0.00629	0.92387
0.00739	0.92421
0.00977	0.92425

REPORT

TURBO PROPULSION LABORATOR'

REDUCED PERFORMANCE DATA OF TURBINE FR

TURBINE TYPE MOD II CONFIGURATION RADIAL ROTOR

TEST RUN NO. 78 DATE OF TEST

	POINT	PRESSURE RATIO	ISENTROPIC HEAD COEFF. (R=4.125 IN.)	EFFICIENCY TOT-STATIC PERCENT	REFERRED FLOW RATE LBM/SEC
ΔX = 0.200"	1	1.2967	3.0462	79.01	3.1018
	2	1.2994	2.5066	77.56	3.0773
	3	1.2990	1.8987	74.12	3.0632
	4	1.2994	1.3403	63.04	3.0864
FOR POINTS 1 TO 4 AVG. PRESSURE RATIO= 1.2986 , MAX.					
ΔX = 0.410"	5	1.2970	3.0358	79.64	3.0878
	6	1.2997	2.5119	78.61	3.0728
	7	1.2994	1.9216	74.95	3.0696
	8	1.2994	1.3445	63.82	3.0865
FOR POINTS 5 TO 8 AVG. PRESSURE RATIO= 1.2989 , MAX.					
ΔX = 1.000"	9	1.2990	3.0231	79.91	3.0929
	10	1.3004	2.5241	78.79	3.0793
	11	1.2997	1.9061	75.72	3.0688
	12	1.2970	1.3271	64.31	3.0773
FOR POINTS 9 TO 12 AVG. PRESSURE RATIO= 1.2990 , MAX.					

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13. ABSTRACT

This thesis was undertaken to determine the effects of axial and radial clearances on the performance of a single stage turbine with blunt leading edges and non-twisted blades. A series of tests was conducted on the so-called Mod II Turbine using the Transonic Turbine Test Rig of the Turbo-Propulsion Laboratory, Department of Aeronautics, of the Naval Postgraduate School. The results of these tests are presented together with a comparison of the experimental results and results predicted by a three-dimensional turbine performance calculating method. In addition, measured flow conditions upstream of the stator, between the stator and the rotor, and at the rotor discharge are presented and compared with predicted values.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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axial clearance						
radial clearance						
blunt blades						